Millennial Physics at Fermilab

The high energy physics program at the U.S. Premier platform for

DISCOVERY

- Introduction
- Standard Model
- Accelerator complex and detectors
- Remembrance of Things Past
  with an emphasis on the top quark
- The future

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what's coming:

I'm going to present the Fermilab proton-antiproton collider program in two lectures, past and future:

"Run I", from 1193-1996, L = 100 pb^{-1}
"RunIIa", from 3/01 - ~03, L ~ 3,000-5,000 pb^{-1}
"RunIIb", from ~03 - LHC physics, L ~ 20,000 pb^{-1}

Lecture 1: A review of the physics of the Tevatron Collider in its first running

- introduction to the Standard Model of elementary particle physics
- introduction to the accelerator and the experiments

Lecture 2: Results and prospects

- Run I results
- Run II prospects

Lecture 2: Fermilab Collider Physics: Results and Prospects

Chip Brock, Michigan State University
2001

Run I

CDF’s second run…DØ’s first.

Run I physics, a (tiny) snapshot

Top quark– Discovery!

$m_t = 174.3 \pm 3.2\ (\mathrm{stat}) \pm 4.0\ (\mathrm{sys})\ \mathrm{GeV}/c^2$

- **Beginnings of detailed studies (cross sections, dist^{ns}, BR, etc.)**

W/Z bosons

$M_W = 80.45 \pm 0.063\ \mathrm{GeV}/c^2$

V-V-V couplings studied

W/Z + soft gluon radiation

unanticipated precision

Bottom quarks – a new field

100's B → J/□ - K_S

B_C discovered

Production *□'s & BR's*

Quantum Chromodynamics

Substructure probed, 10^{-18} cm

Radiative corrections confirmed

Colorless exchange - Pomeron

Exotic physics – searches

supersymmetry

leptoquarks

Higgs boson

additional W/Z's

Over 250 papers published in PRL, PR, NP

The Top Quark at Fermilab

it's big.

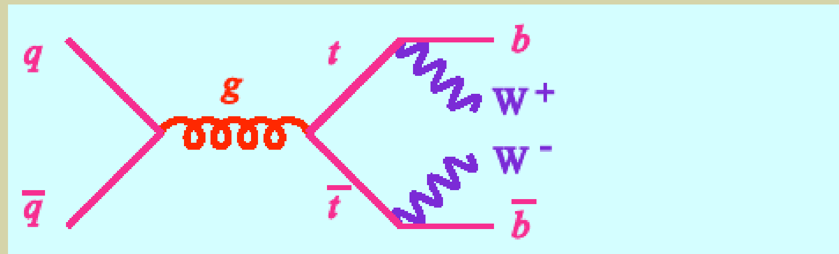
The TOP quark, 1

Who ordered that? – the extraordinary mass of 175 x m_p distorts one's expected picture of (just) a quark…

The decay of a quark, Q, with $m_Q > M_W + m_q$ is straightforward:

$$\Gamma(Q \to qW^+) = \frac{G_F m_Q^3}{8\pi\sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{m_Q^2}\right)^2 \left(1 + \frac{2M_W^2}{m_Q^2}\right)$$

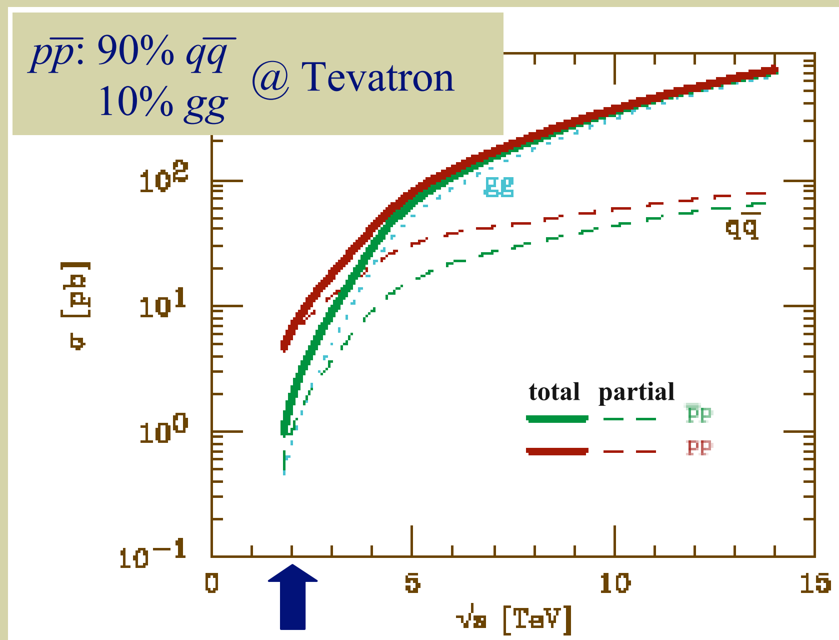
One power of G_F



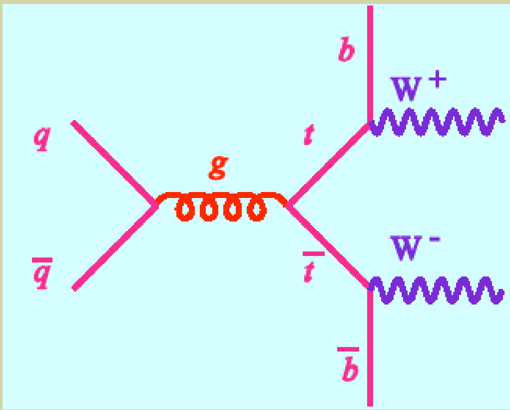
V_{tb} is an element of the quark mixing matrix, bounded by the requirement of Unitarity and weak interaction phenomenology.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9745 - 0.9760 & 0.217 - 0.224 & 0.0018 - 0.0045 \\ 0.217 - 0.224 & 0.9737 - 0.9753 & 0.036 - 0.042 \\ 0.004 - 0.013 & 0.035 - 0.042 & 0.9991 - 0.9994 \end{pmatrix}$$

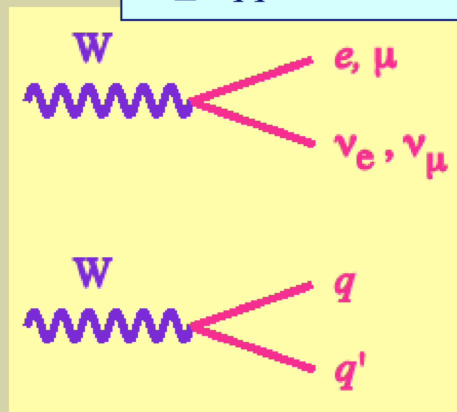
SO, the fraction of decay of $t \to W\,b$ is almost 100%.
SO, $\tau_{top} \approx 0.4 \times 10^{-24}$ s … QCD confinement scale ≈ $1/\Lambda_{QCD} \approx$ few x 10^{-24} s
Which means…top quarks decay before they form top-mesons…bare fermion… unprecedented and surely a clue to something?



TOP manifests itself three ways, depending on the W decay:



bℓ□bqq’ 30% “lepton + jets”

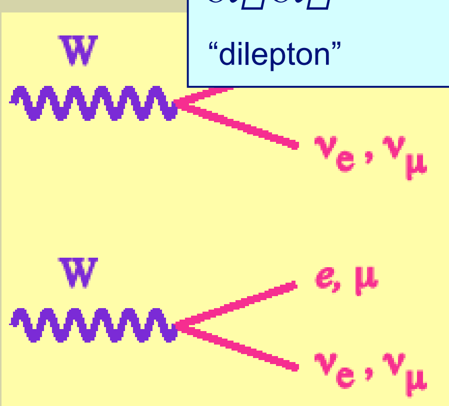


Charged lepton
Missing energy
2 jets
2 b quarks

serious backgrounds: QCD *Wjjbb w/* S/B ~2/1, 4/1 with *b* tagging

But wait, there’s more:

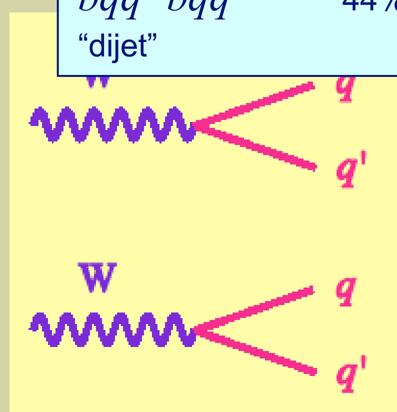
bℓ□bℓ□ 5%
“dilepton”



2 Charged leptons
Missing energy
no jets
2 b quarks

low backgrounds: QCD *Wjjbb*, (fake e, missing j) w/ S/B~3-4/1

bqq’ bqq’ 44%
“dijet”



no lepton
no Missing energy
4 jets
2 b quarks

Huge backgrounds: QCD multijets w/ S/B~1/1

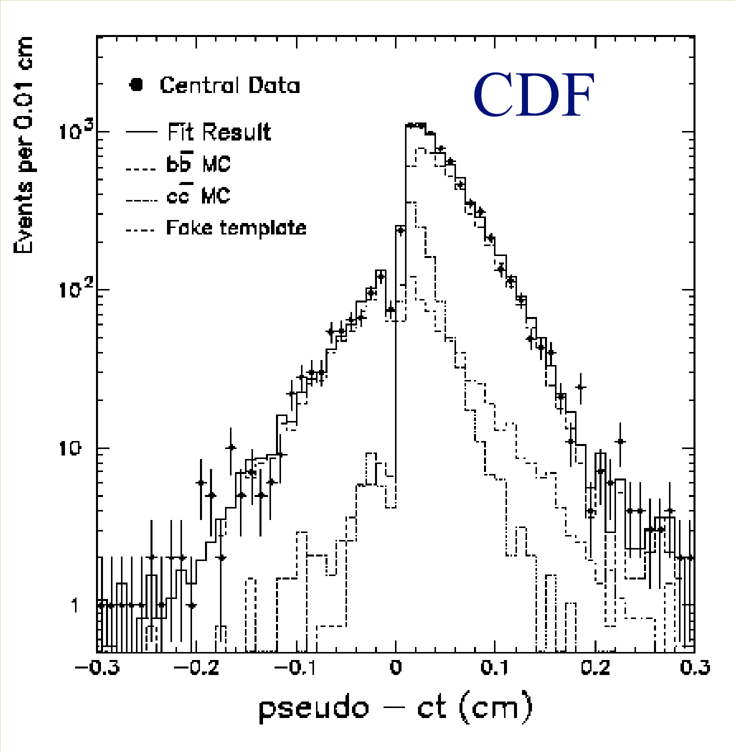
Getting to the bottom of the top quark…

- We have a magical key…
- The b quark lives a long time…$\tau_b \approx 1.5$ ps

Si vertex detectors are magic

1. lifetime is long enough to measure
2. Important for top physics
3. Important in it's own right for B hadron physics
4. now a precision industry

- Efficiency for 1 Si vertexing (**SVX**) tag is ϵ ~50% and essentially $p(b)$ independent
- Can double tag with ϵ> 40%
- also can detect the presence of a soft lepton (**SLT**) from $b \longrightarrow c\,\ell\,\nu$

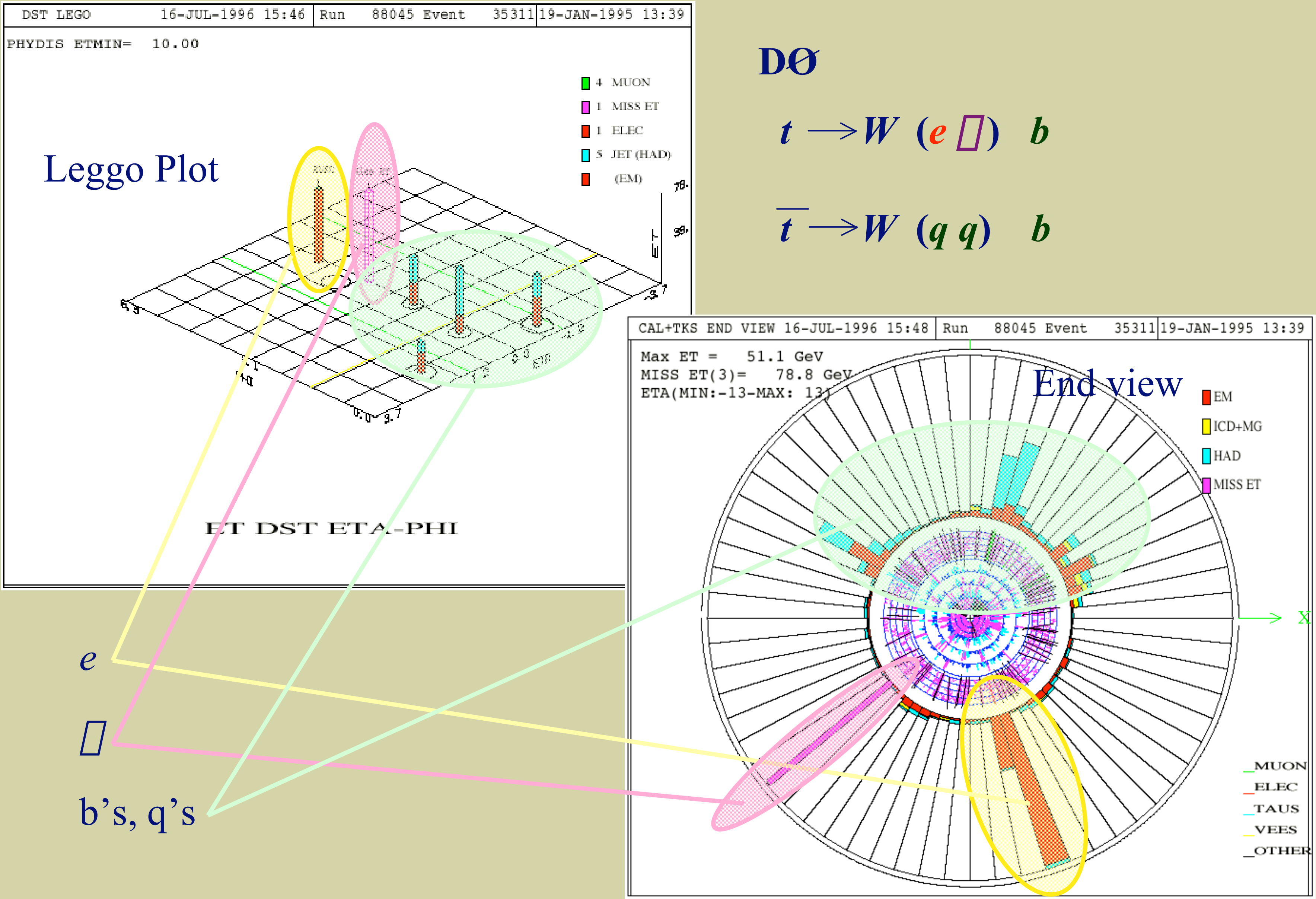


Top, revealed

DØ

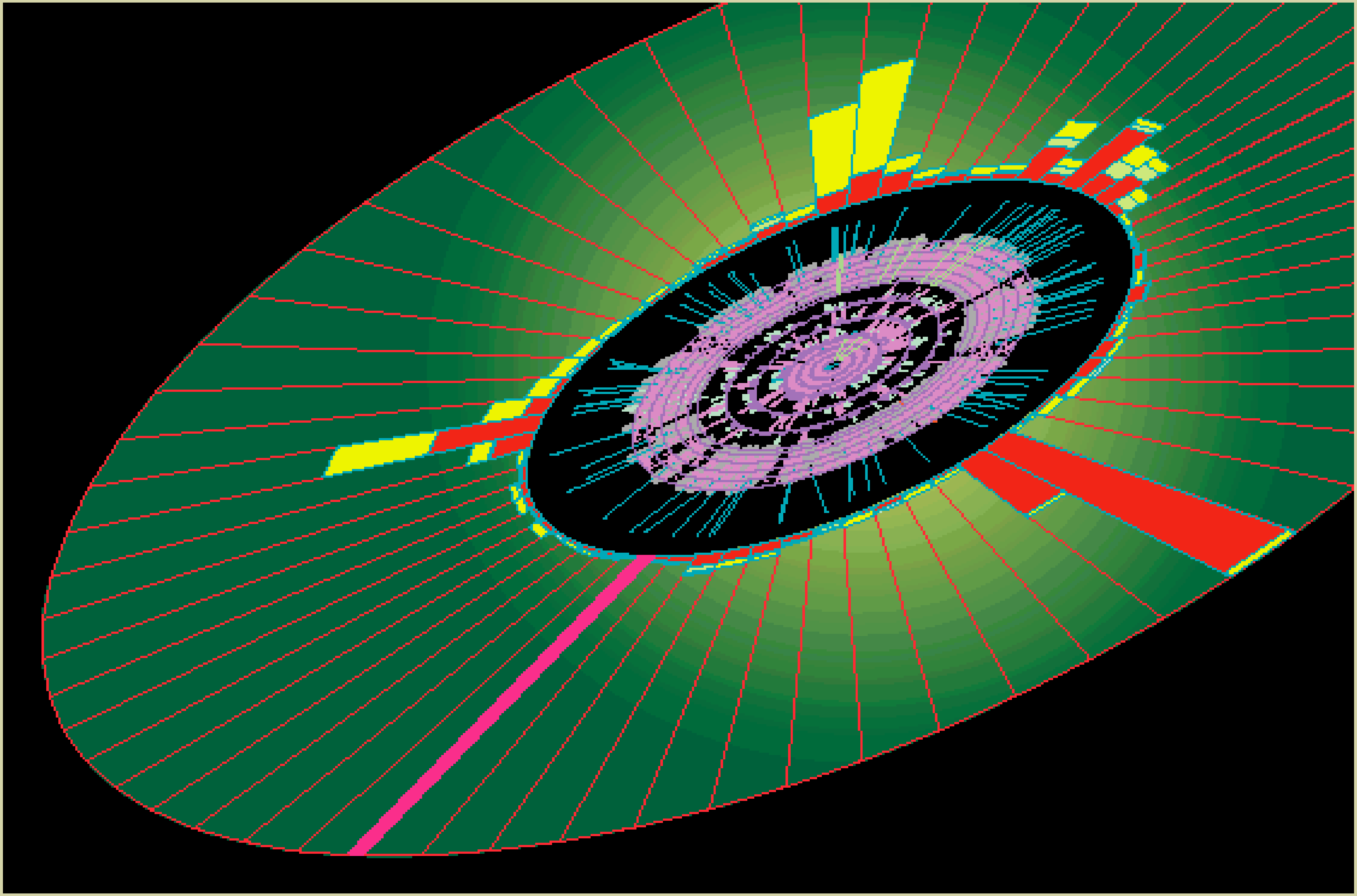
$t \longrightarrow W\ (e\ □)\ \ b$

$\bar{t} \longrightarrow W\ (q\ q)\ \ b$

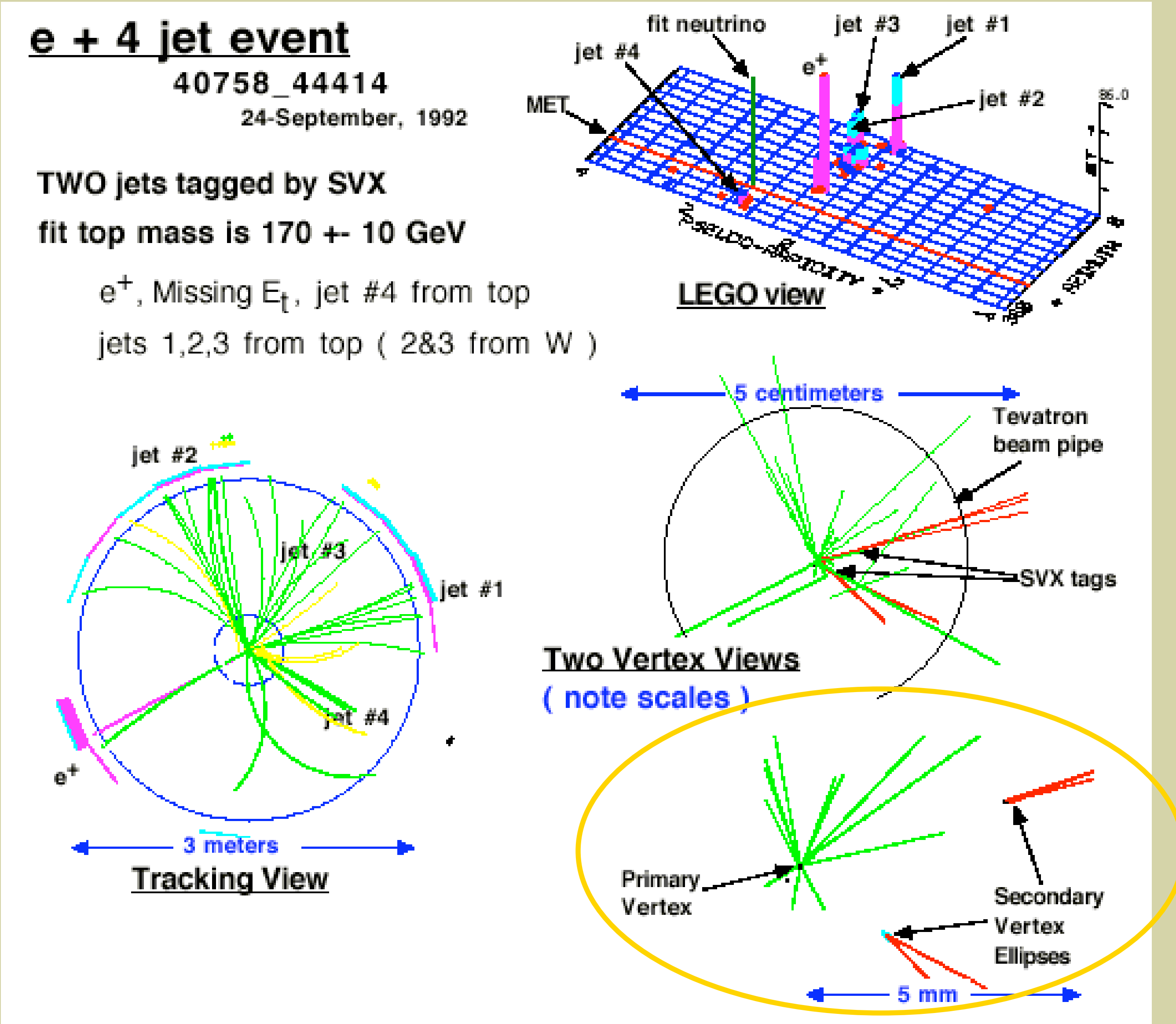


Chip Brock, Michigan State University
2001

DØ top as art



Top's bare bottom revealed by CDF



seeing the bottom quark decay

Top quark physics: cross section

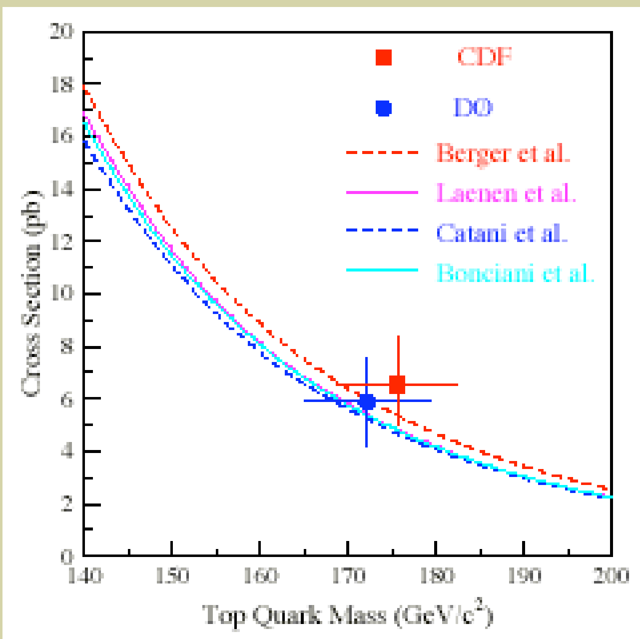
A cross section is a basic measurement:

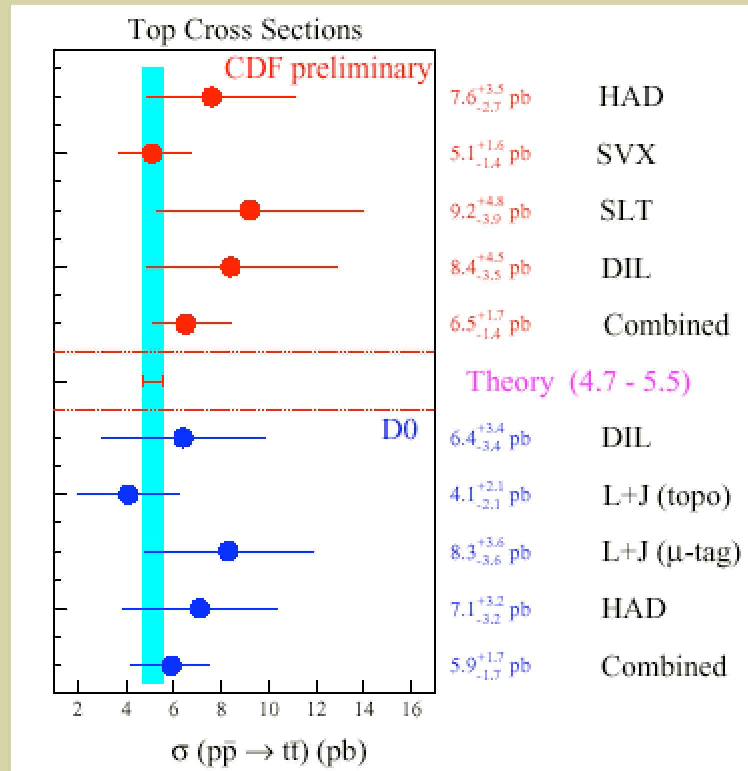
$$\sigma(p\bar{p} \to X \to channel_i) = \frac{N^i_{obs} - N^{i}_{background}}{\varepsilon_i \cdot \int \mathcal{L}\,dt}$$

A complicated theoretical effort for comparison

- Stresses QCD understanding at a deep level
- Heavy quark QCD calculations are tough

CDF: $6.5^{+1.7}_{-1.4}$ pb
DO: 5.9 ± 1.7 pb





Top quark physics: mass determination

Full kinematical fitting of lepton+jets, dilepton, all jets candidates

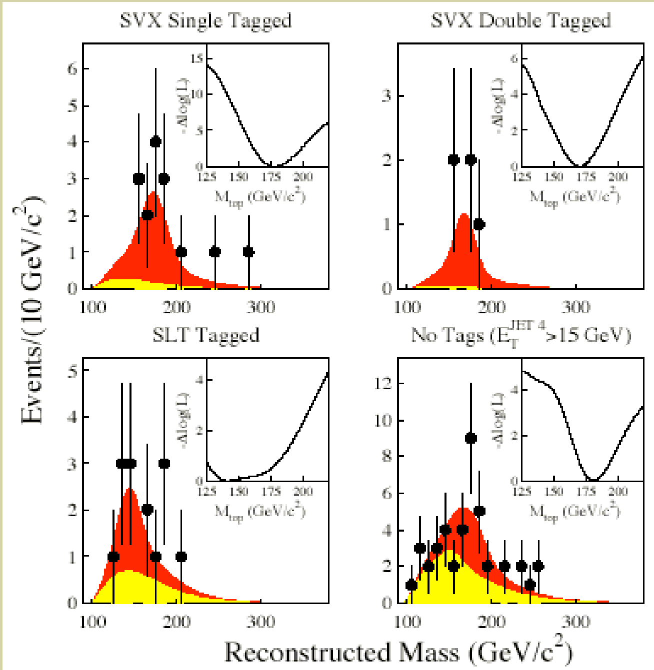
- A serious challenge for background simulation
- in particular, the QCD production of *W*+ multiple jets w/b's

Channel	DO	DO	CDF	CDF
	sample	***bckgnd***	***sample***	***bckgnd***
Di-lepton	5	1.4 ± 0.4	9	2.4 ± 0.5
Lep+jets SVX			34	9.2 ± 1.5
Lep+jets SLT	11	2.4 ± 0.5	40	22.6 ± 2.8
Lep+jets top	19	8.7 ± 1.7		
All jets	41	24.8 ± 2.4	184	142 ± 12
en	4	1.2 ± 0.4		
et, mt			4	≈2

Very sophisticated likelihood combinations of samples are now done

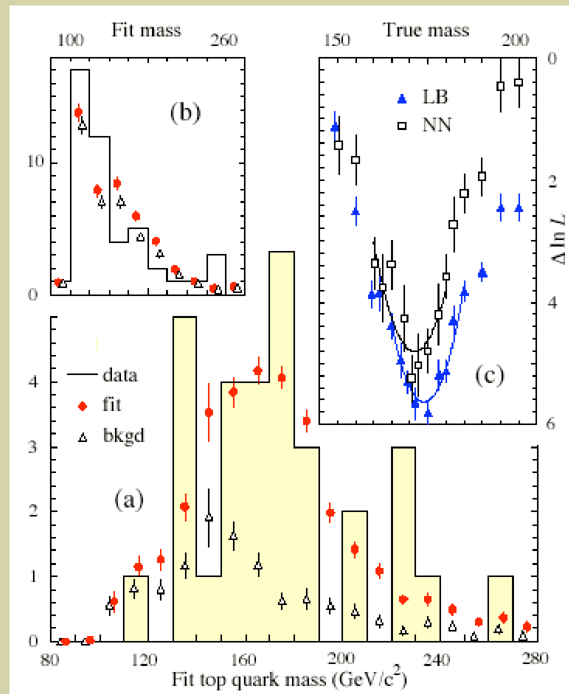
- eg., CDF combined 4 indepdendent samples for their best result
- DO employs complicated kinematical and topological cuts

lepton plus jets mass results



systematics	(GeV/c^2)
jet energy determination	4.0
bckgnd model	2.5
signal model	1.9
fitting tech.	1.5
cal. noise	1.3
Total	5.5

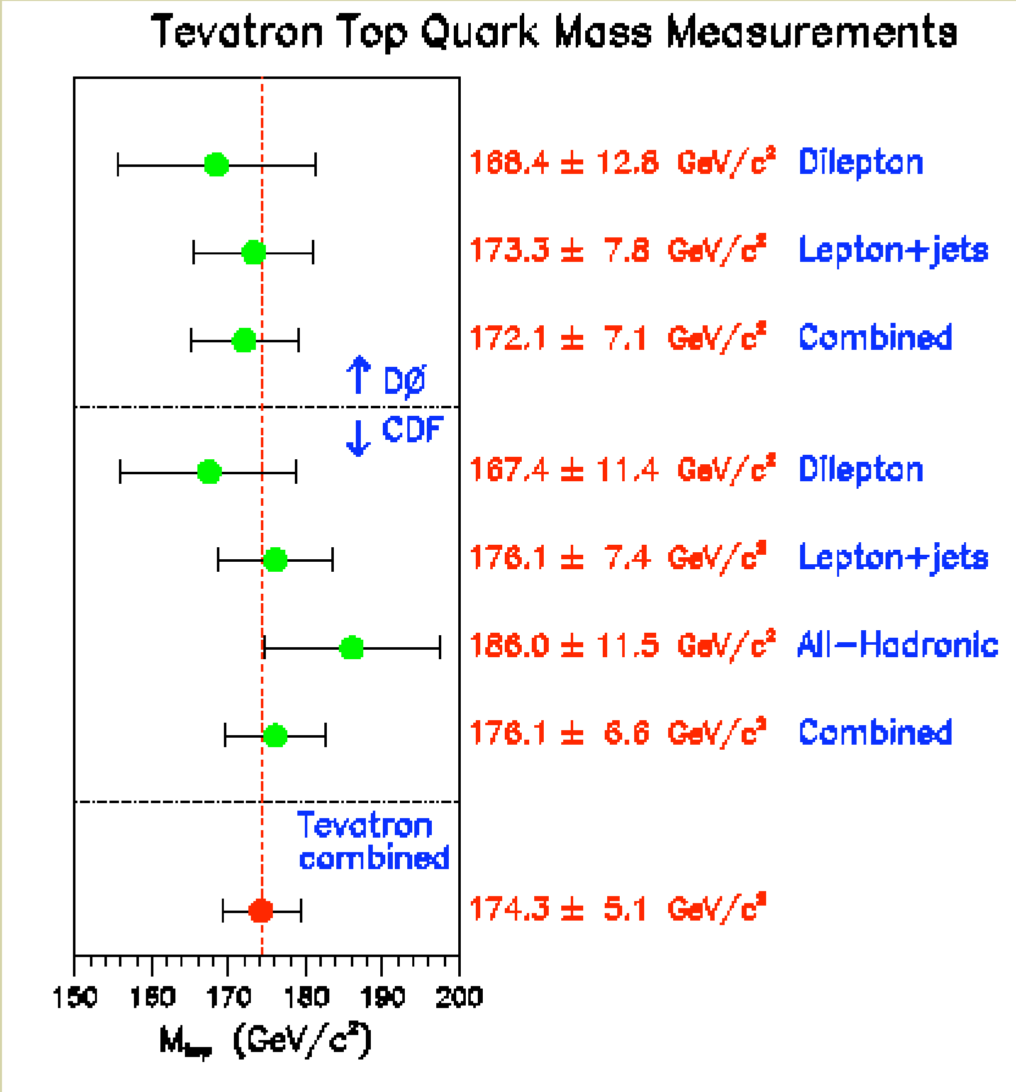
DØ



systematics	(GeV/c^2)
jet energy determination	4.4
ISR & FSR	2.6
bckgnd shape	1.3
b-tag bias	0.4
pdf	0.3
Total	5.3

CDF

Top Quark Mass

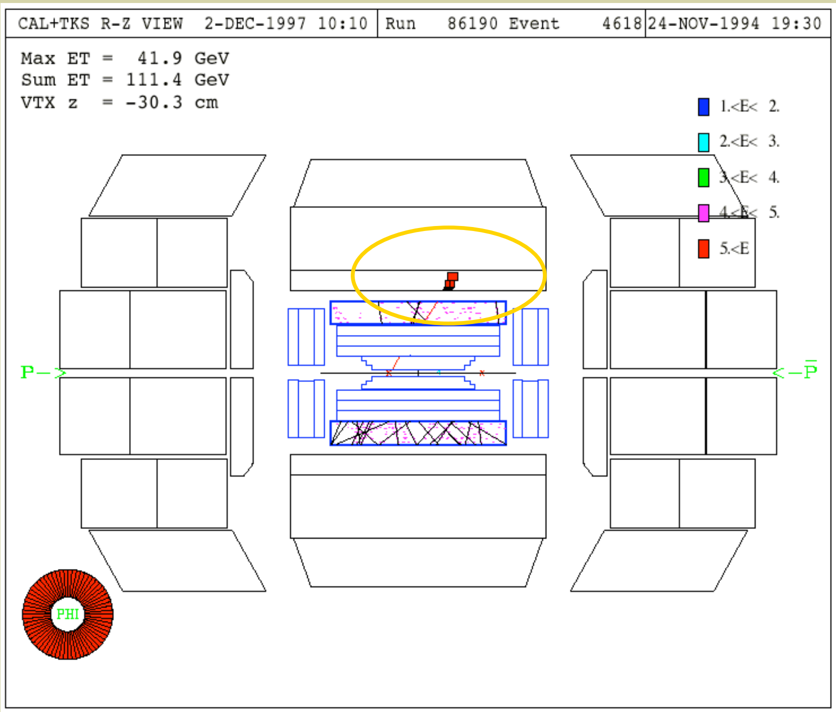


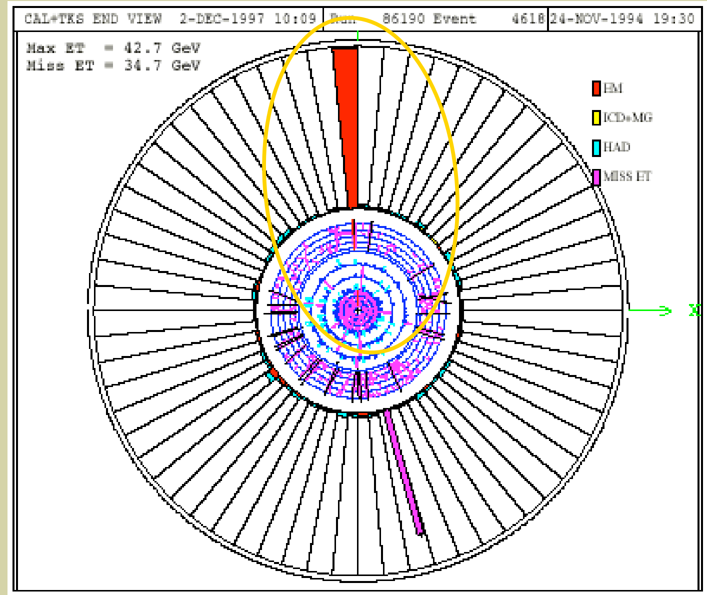
Electroweak Physics

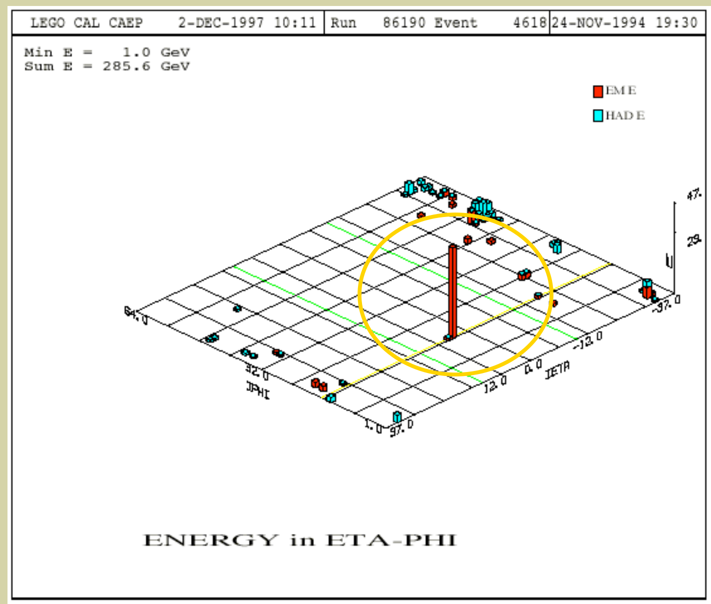
fraction of a percent experiments with a 5500 ton microscope

Remember, if you don't see anything, it's a neutrino…

DØ $W \longrightarrow e\nu$

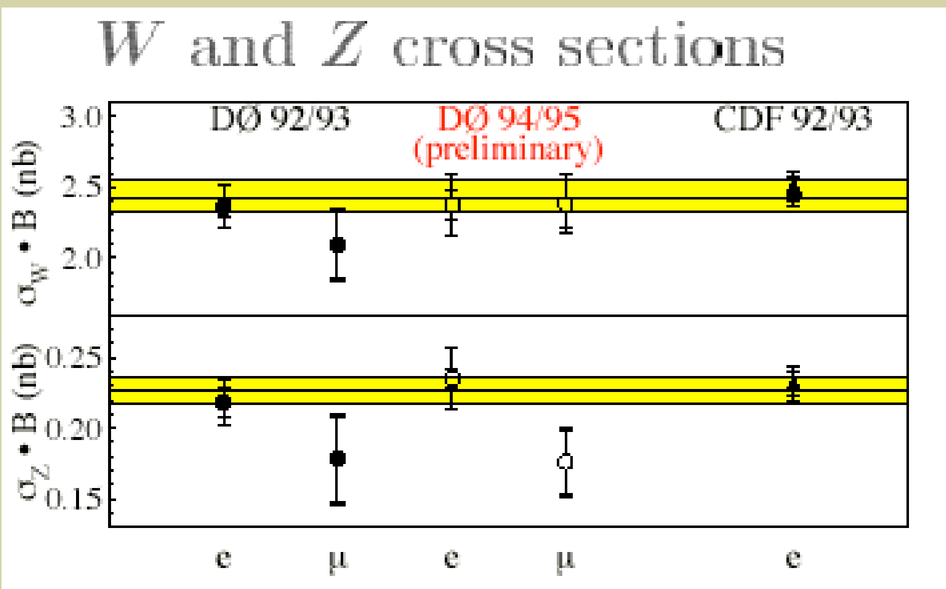






The physics of W's, γs, and Z's

- σ(W,Z) & Γ_W determination
  - **Cross section – strong test of QCD**
- "tri-boson couplings"
  - **Testing the gauge theory at the vertices – new physics would reveal itself here**
- Mass determination (remember the loops?)
  - **Requires precision of ±0.06%**



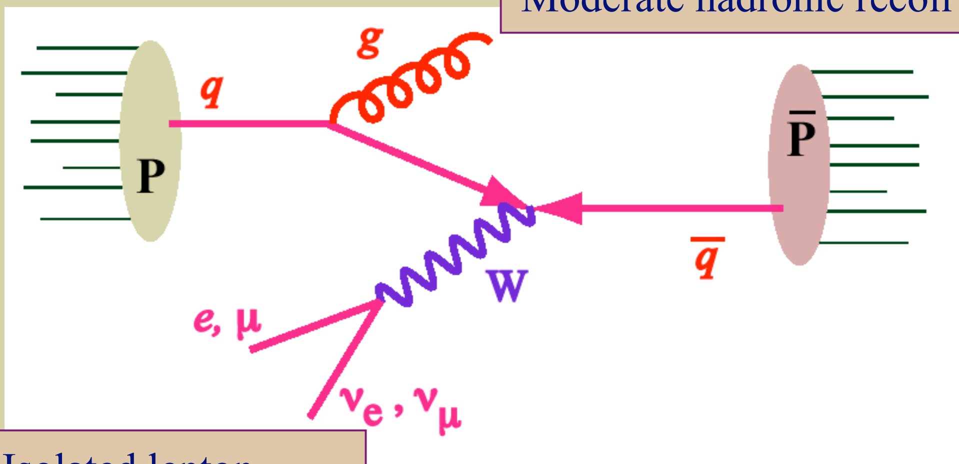
Theoretical prediction: $O(\alpha^2_S)$ Hamberg, van Neerven, Matsuura; van Neerven & Zijlstra

Dominant uncertainties:
Luminosity, ≈ 8% (expt) &
Parton distribution functions, ≈ 3% (theory)

W mass determination

A tricky measurement

Moderate hadronic recoil (~5 GeV/c)

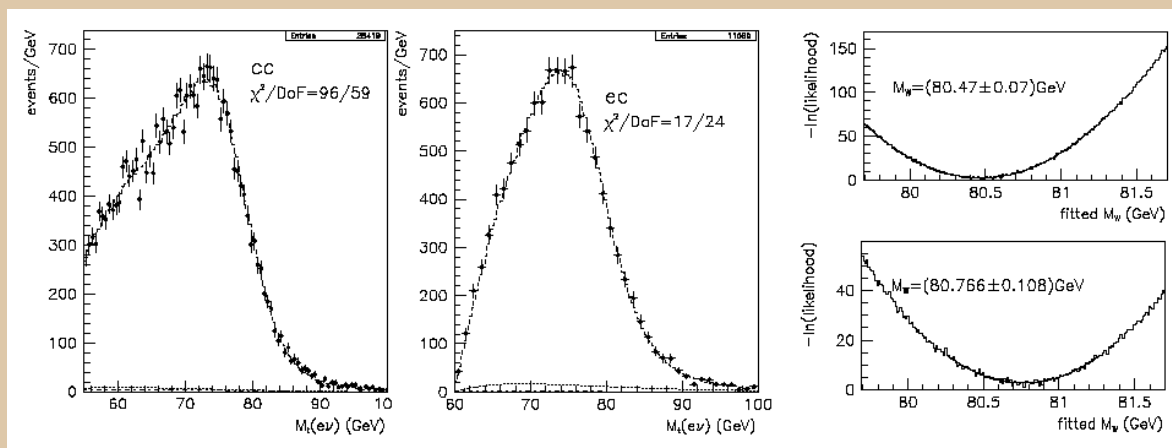


Isolated lepton
Missing momentum

exploit the 2 body decay kinematics, identify the sharp "Jacobian" edge by defining the "transverse mass"

$$m_T^2(\ell,\nu_\ell) = \left(|\vec{p}_\ell| + |\vec{p}_{\nu_\ell}|\right)^2 - \left(\vec{p}_\ell + \vec{p}_{\nu_\ell}\right)^2$$
$$= 2E_T^\ell E_T^{\nu_\ell}\left(1 - \cos\phi_{\ell\nu}\right)$$

$$\frac{d\hat{\sigma}}{dm_T^2} = \frac{|V_{qq'}|^2}{4\pi}\left(\frac{G_F M_W^2}{\sqrt{2}}\right)^2 \frac{1}{\left(\hat{s} - M_W^2\right)^2 + \left(\Gamma_W M_W\right)^2} \frac{2 - m_T^2\hat{s}}{\left(1 - m_T^2/\hat{s}\right)^{1/2}}$$



DØ latest

M_W = 80.474 ± 0.093 GeV/c² DO
= 80.433 ± 0.079 GeV/c² CDF
= 80.450 ± 0.063 GeV/c² Tevatron

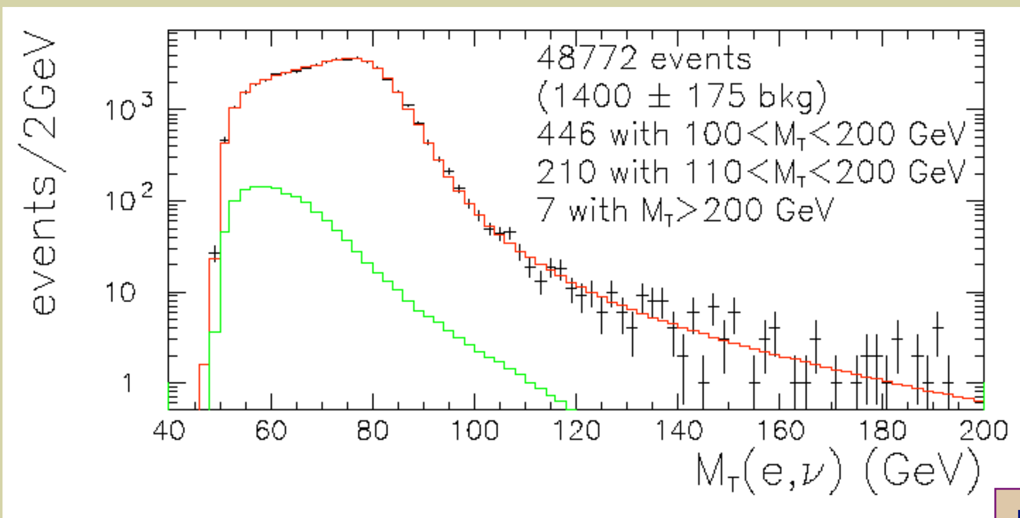
The full width of the W can be measured in three ways
(SM: Γ_W = 2.077 ± 0.014 GeV)

- Indirectly from:

$$R_{W/Z} = \frac{\sigma_W \cdot BR(W \to \ell\nu_\ell)}{\sigma_Z \cdot BR(Z \to \ell\ell)} = \frac{\sigma_W \cdot \Gamma(W \to \ell\nu_\ell)}{\sigma_Z \cdot BR(Z \to \ell\ell) \cdot \Gamma_W}$$

$$\Gamma_W = 2.130 \pm 0.56 \text{ GeV} \quad \text{DØ (new)}$$
$$= 2.064 \pm 0.084 \text{ GeV CDF}$$

- Directly from the tail of the m_T distribution:

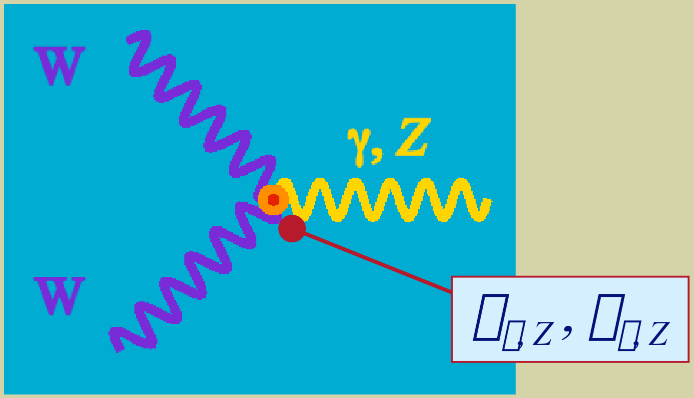


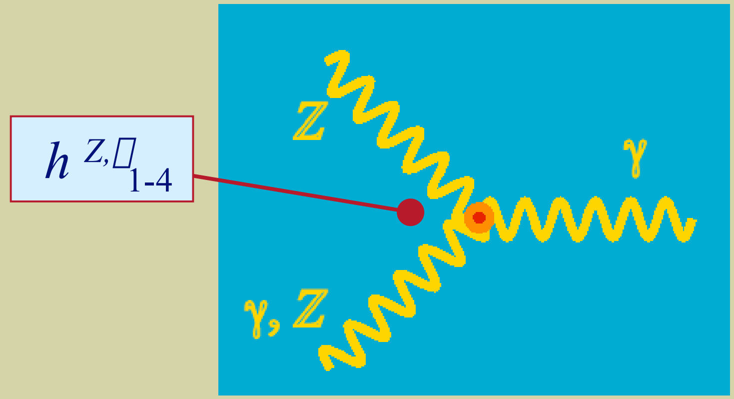
$$\Gamma_W = 2.19 \pm 0.19 \text{ GeV CDF}$$

- Simultaneously, in 2 parameter fit with M_W

Tri-boson couplings

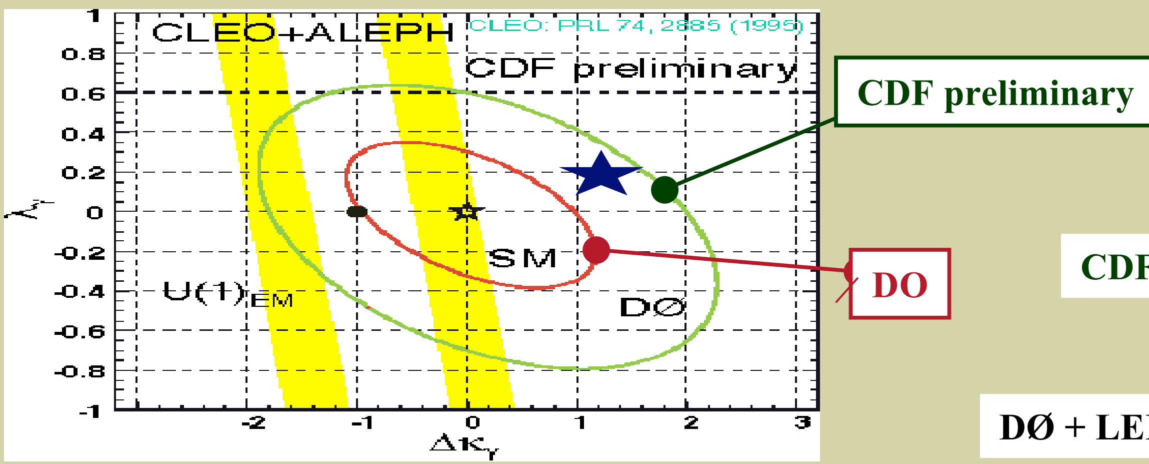
The IVB can couple to one-another due to the non-Abelian nature of the Yang-Mills prescription





Measurements characterized as parameterized deviations from SM...an anomolous magnetic or electric moment

Standard Model values: $k_{g,\,Z} = 1$; $l_{g,\,Z} = 0$; $h^{Z,g}_{1\text{-}4} = 0$



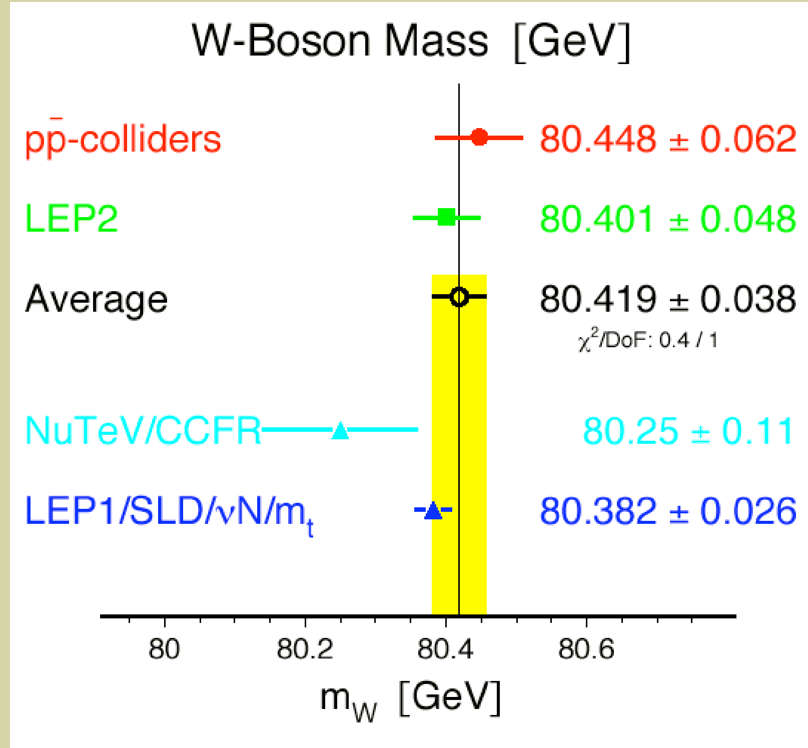
DØ: $-0.93 < \kappa_\gamma - 1 < 0.94$, $-0.31 < \lambda_\gamma < 0.29$

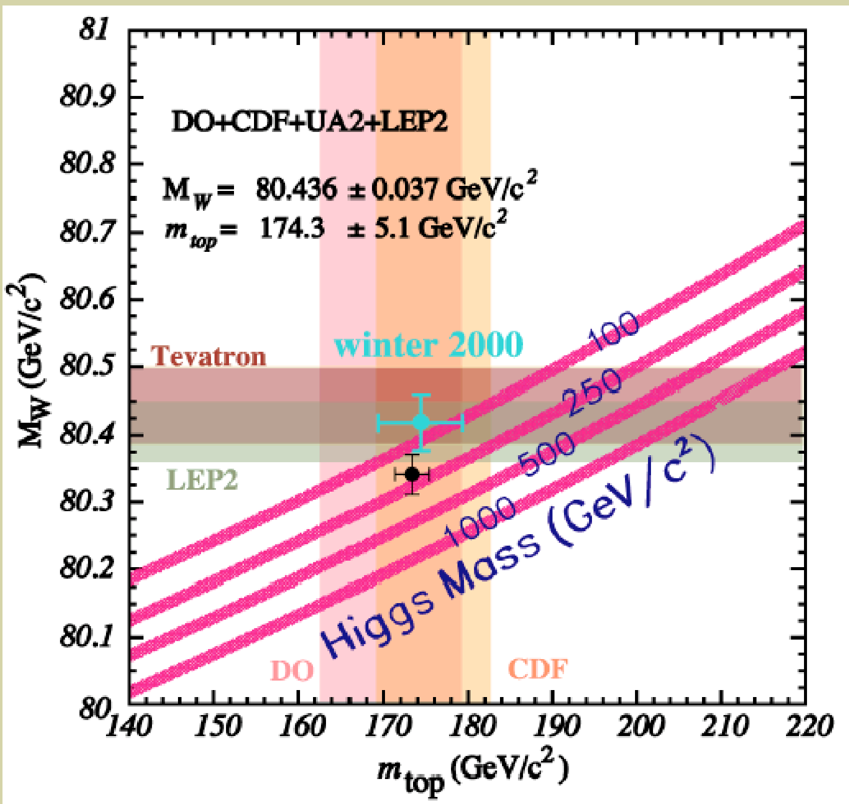
CDF preliminary: $-1.8 < \kappa_\gamma - 1 < 0.94$, $-0.7 < \lambda_\gamma < 0.6$

DØ + LEP @ 68% CL: $\Delta\kappa_\gamma = 0.13 \pm 0.14$, $\lambda_\gamma = 0.6 \pm 0.07$

The Standard Model Connection

- LEP2 has final results
- NuTeV (□N DIS) has preliminary results
  - $\sin^2$□$_W$, interpreted as M_W





Run2 uncertainties intentionally plotted @ 1996 central values

Good reminder of what 1 □ means & reason for growing excitement at Fermilab

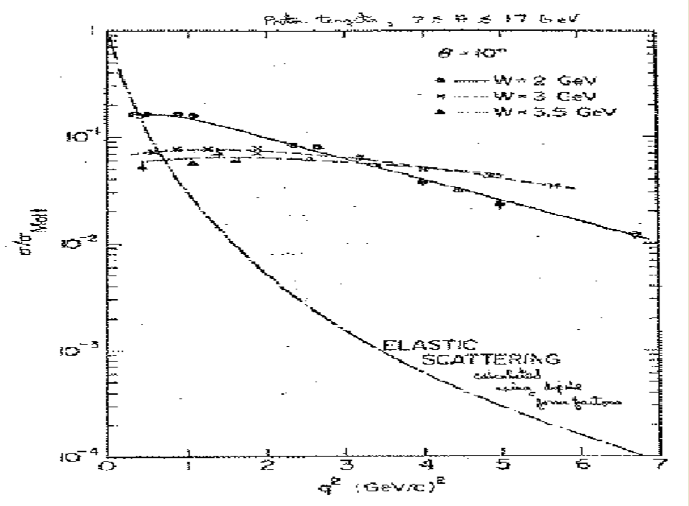
IT'S A DIFFERENT GAME NOW – THE SM HIGGS BOSON APPEARS TO BE *LIGHT*

Quantum Chromodynamics

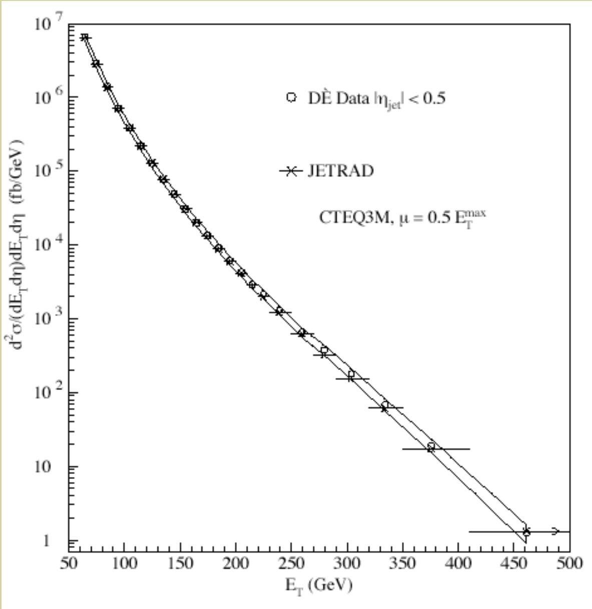
the glue that holds us together: it’s everywhere

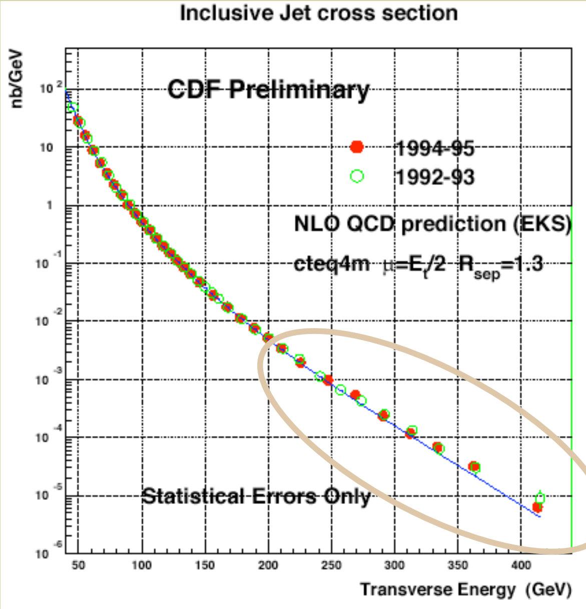
Study of strong interactions

Most basic measurement–the search for substructure…akin to the original discovery of partons at SLAC

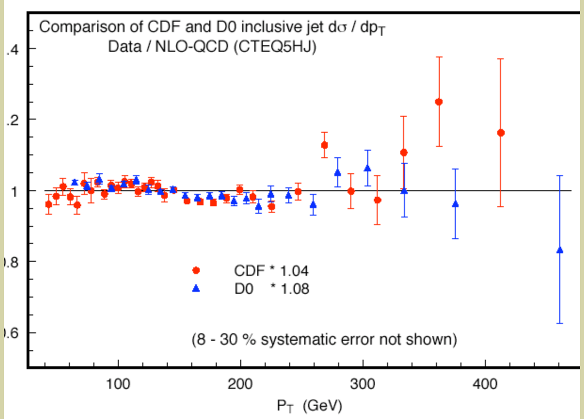


Controversial for a while: was there an excess at high jet E_T?
could be evidence for substructure



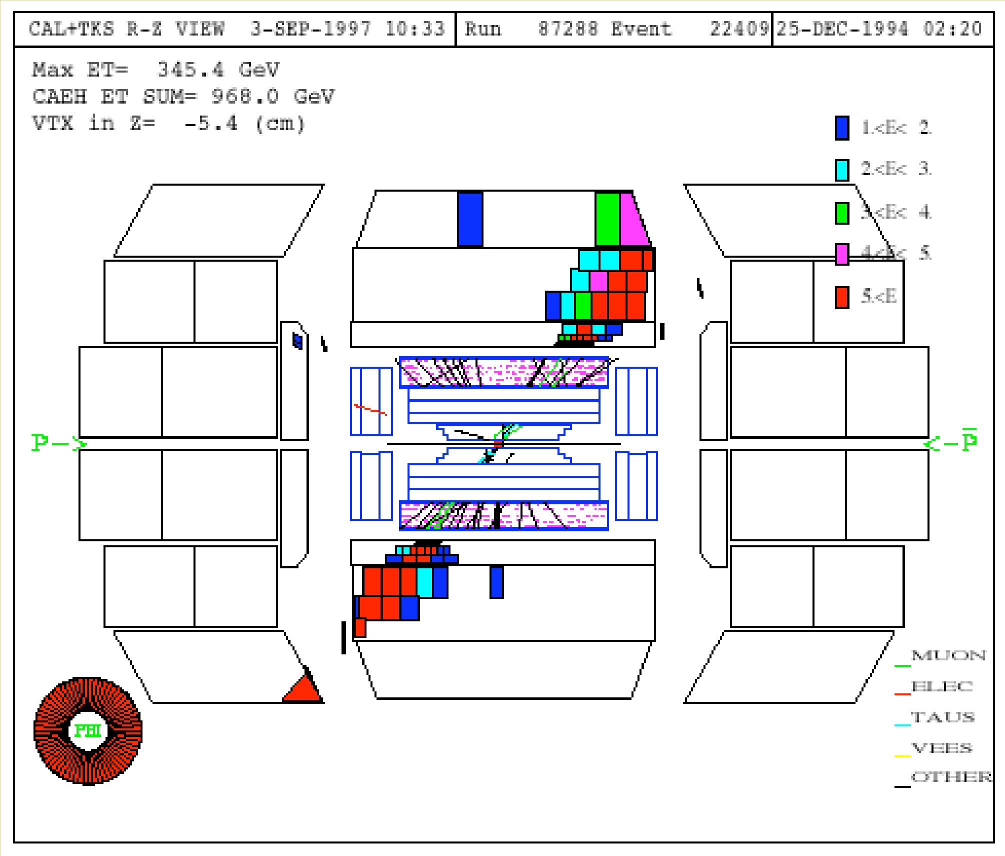


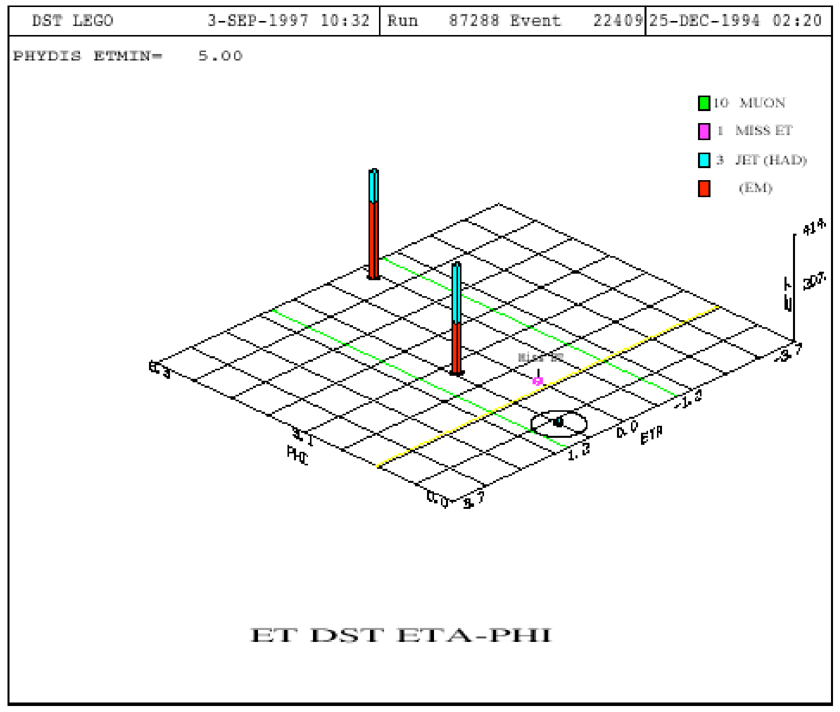
proof of principle: parton distribution set that works



False alarm? Both experiments agree…both agree with theory. Probably a reminder of how hard it is to predict the gluon distribution in the proton

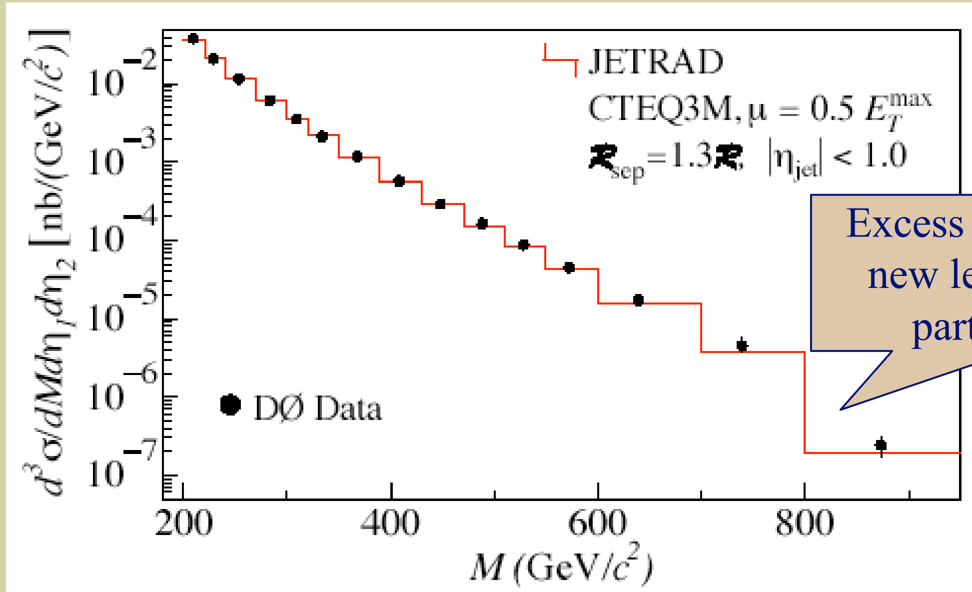
Highest E_T jet event in DO E_T = 475 GeV





Much more…

Dijet mass spectrum - another substructure search

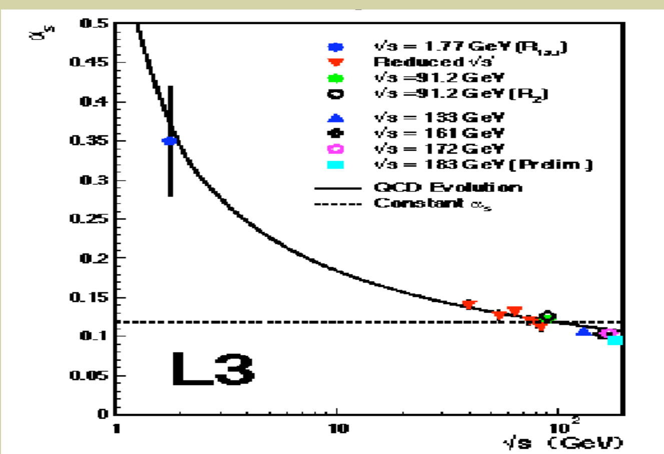


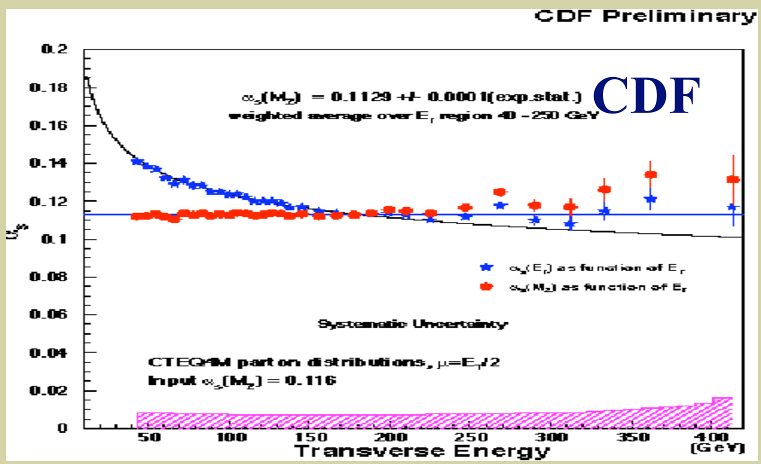
Excess would suggest a new length scale in 2 parton collisions

α_S **running determination**

at an electron collider

…at a hadron collider!



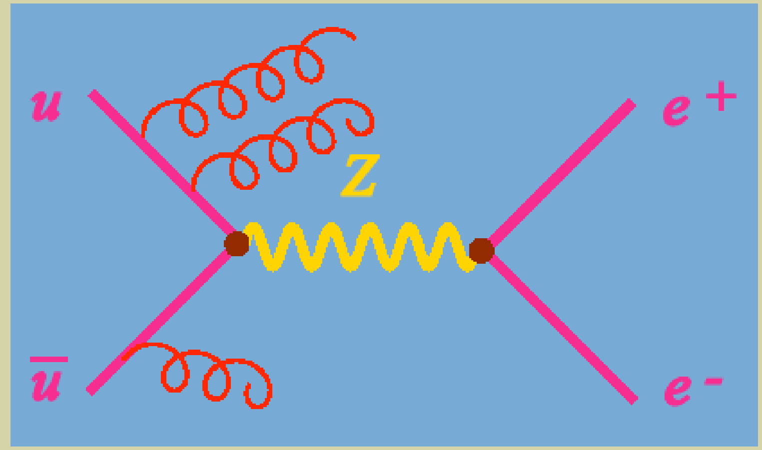


From CDF inclusive jets:

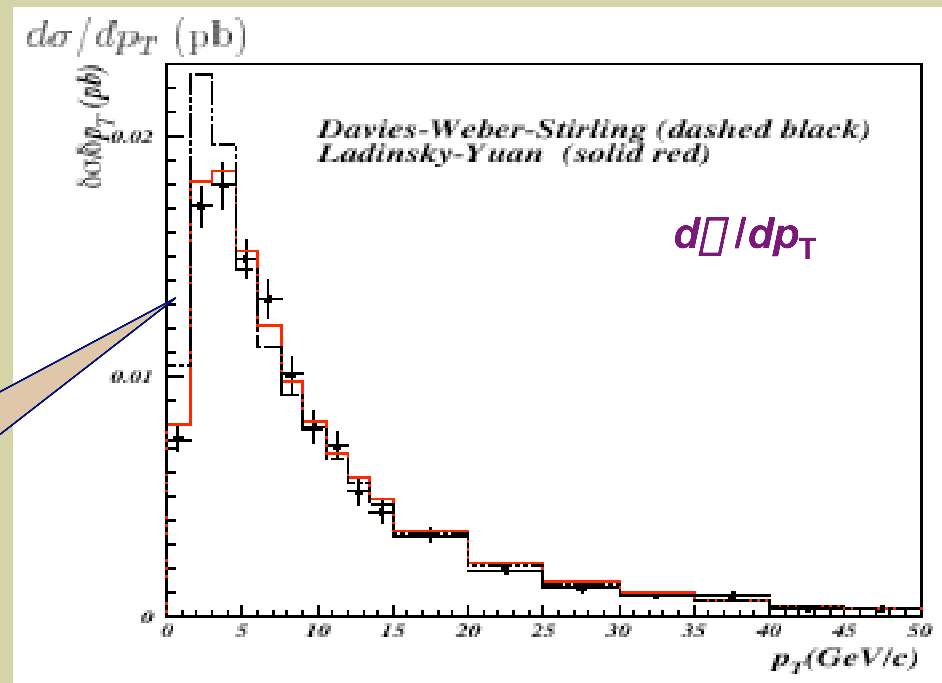
Blue shows the running of the strong coupling, $\alpha_S(E)$, with changing scale, E_T. Red, shows the lack of dependence at a fixed scale. Not absolute $\alpha_S(E)$.

Gluons are cheap…

Indeed, they radiate like mad from quarks and gluons and accounting for them is complicated in processes in which there are two length scales
…like the $d\sigma/dp_T$ for *W* and *Z* production, or □ production



Must deal with ∞ series of divergences: $\ln(Q^2/p^2_T)$



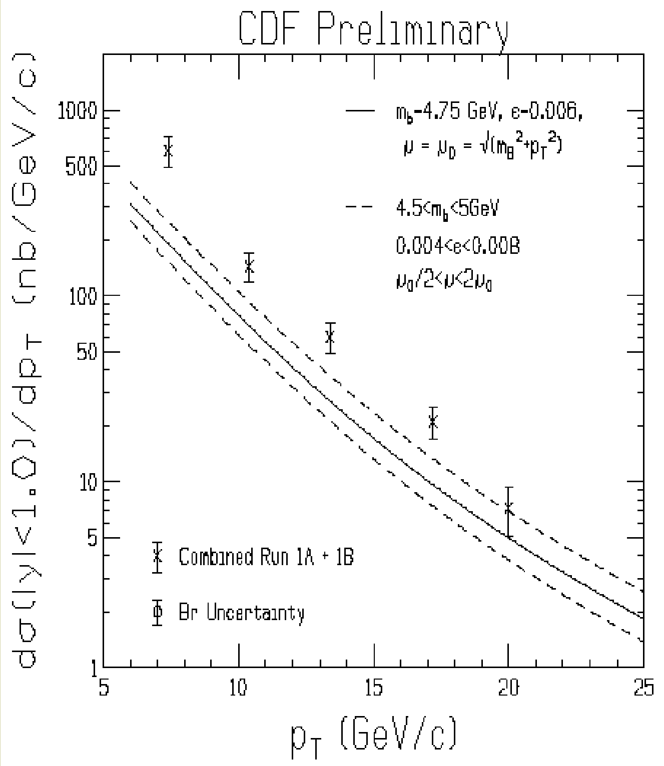
Turn-over, the effect of QCD radiative corrections and infinite gluon resummation

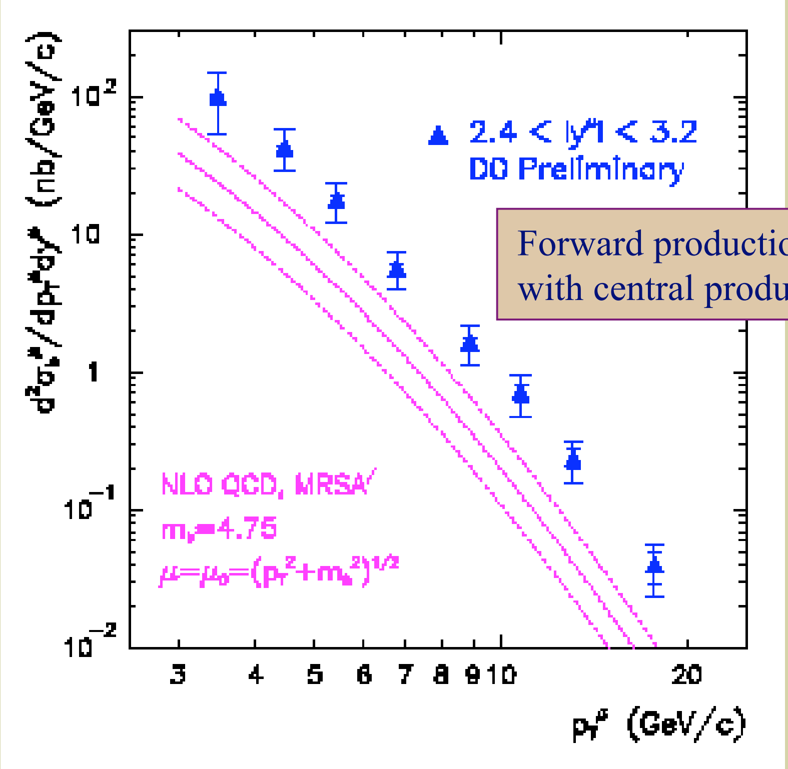
Bottom Quark Physics

figuring out why we’re matter and not antimatter - or both!

B Physics – HEP with microbarns

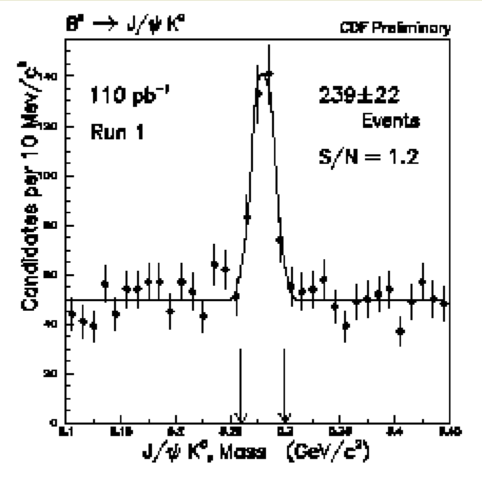
Both experiments study B mesons





Forward production agrees with central production

CDF's SVX tags the detached vertices of the B's



this is beautiful physics

B ut wait, there's more

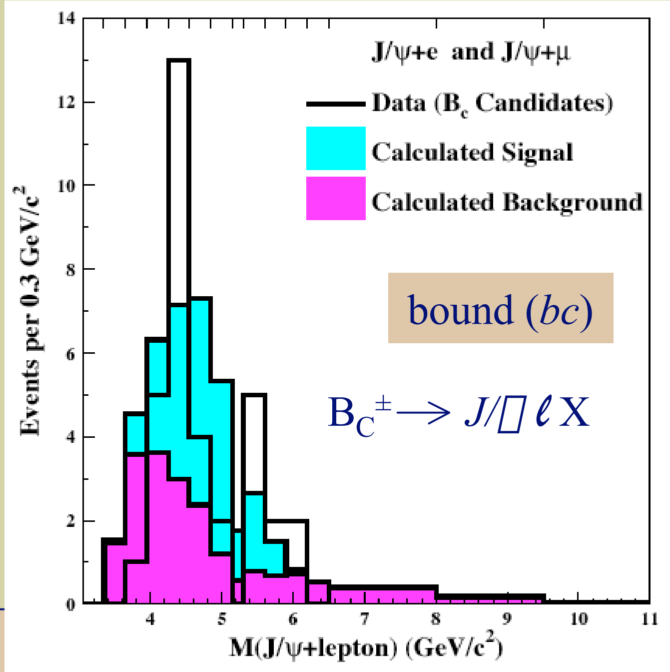
CDF: lifetimes, eg.

$\tau(B^-) = 1.637 \pm 0.058 +0.045/-0.043$ ps
$\tau(B^0) = 1.474 \pm 0.039 +0.052/-0.051$ ps $\Big\}$ $B \to J/\psi\, K$ & $D\, \ell\, X$
$\tau(B^0_s) = 1.34 + 0.23/-0.19 \pm 0.05$ ps B_s $J/\psi \to \phi$
$\tau(\Lambda^0_b) = 1.36 \pm 0.09 +0.06/-0.05$ ps Λ_b $\Lambda_c \to \ell\, \nu$

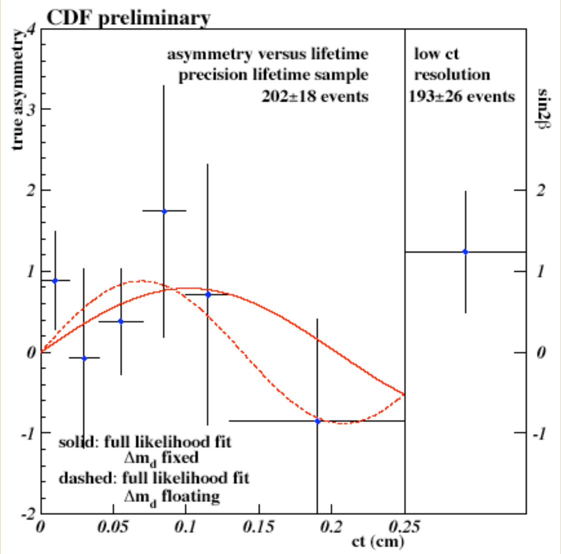
CDF discovered the B_C meson

$M(B_c) = 6.40 \pm 0.39 \pm 0.13$ GeV/c^2

$\tau(B_c) = 0.46 \, {}^{+0.18}_{-0.16} \pm 0.05$ ps



CDF observed and measured $B^0 - \overline{B^0}$ oscillation parameters



$\boxed{B \to J/\psi\, K^0_s}$

Combination of 3 tagging techniques:
SVX "same side" tag
SLT tag
Jet charge tag $\sin 2\beta = 0.79 \, {}^{+0.41}_{-0.44}$

Where the SM predicts 0.66 - 0.84
First observation of CP in the B system, confirming the large expected asymmetry

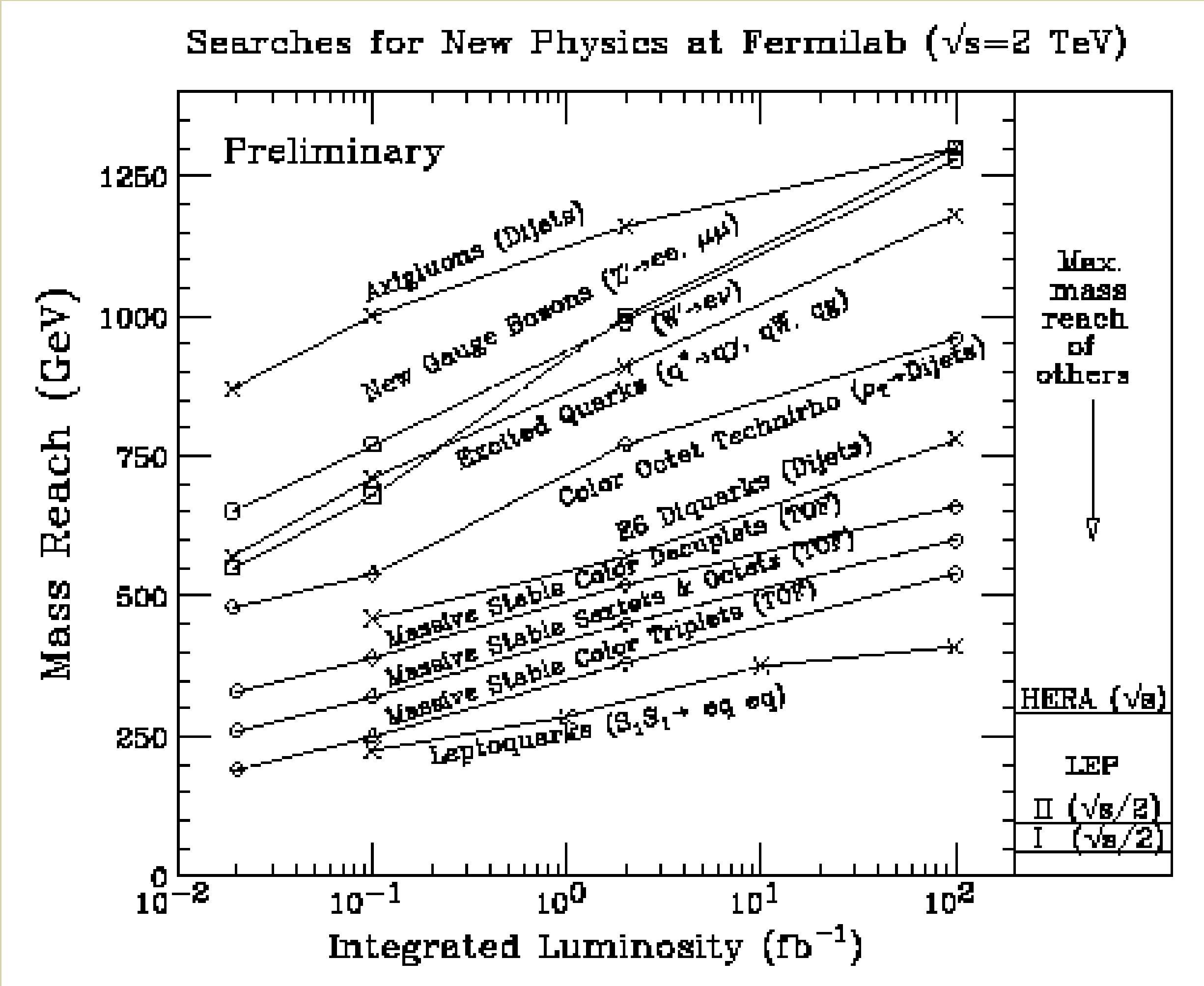
Many extensions of the SM are imaginable

- All must be dealt with systematically

Exotica including:
- Extra gauge bosons
- Leptoquarks (bound lepton-quark states)
- Technicolor

a matter of luminosity...

Measured limits are right on schedule for 100 pb^{-1}



Run II

the standard model has nowhere to hide

Goals of Run II

Accelerator:

- To deliver 10-30 x more integrated luminosity

Experiments:

- To deal with it...and the required upgrades

Physics goals:

- Understand the top quark, measure $\Delta m_t \approx 2$ GeV/c^2
- Determine the cross section to ± 8%
- Determine the W mass to $\Delta M_W \approx 40$ MeV/c^2
- Determine the W width to few %
- Determine $| V_{tb} |$ to ±10%
- Refine B physics measurements, extend rare decay searches
- Extend the reach for compositeness to 500 GeV
- Test NNLO QCD and further study the pomeron
- Extend the search reach for Supersymmetry and exotic phenomena

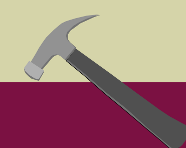
Top quark physics in the future

The TOP quark might be Special…we aim to find out.

With $\int \mathcal{L} dt = 10\ fb^{-1}$, we will:

- determine m_{top} to 1-2 GeV/c^2
- measure $\sigma(tt)$ to 6%
- measure BR($t \to b$) to 5%
- probe for tt resonant states to 1 TeV/c^2
- Michel analysis of top couplings
- isolate EW produced top quarks and:
  - determine σ to 10%
  - determine $\Gamma(t \to Wb)$ to 10%
  - determine V_{tb} to 5%
  - search for anomalous couplings
  - search for CP
- probe for rare decays to 10^{-3} - 10^{-4}

mode	accepted/experiment $2fb^{-1}$	accepted/experiment $10fb^{-1}$
tt produced	16,000	80,000
ℓ + ≥ 3*j* / 1*b tag*	1,800	9,000
ℓ + ≥ 4*j* / 2*b tags*	*600*	*3000*
$\ell\ell$ + 2*j*	200	1,000
EW produced top	330	1,650



Fermilab is a top quark factory

IVB physics

With $\int \mathcal{L}\,dt = 10\ \mathrm{fb}^{-1}$, **we will:**

determine M_W to ~30 MeV/c^2

- which will bound M_H to 40-50% of itself
- (good timing for direct searches)

measure $\Gamma(W)$ to 15 MeV

refine asymmetries (W and Z) and hence, pdf's

limit WWV and $Z\gamma$ couplings

quantify radiation zero in $W\gamma$

search for rare W decays

limit CP violation

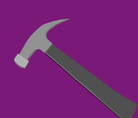
quantify quartic gauge couplings

study resummation in 2 scale problems

- $p_T(W)$, $p_T(\gamma\gamma)$

	accepted/experiment	
channel	2fb^{-1}	10fb^{-1}
$W\to e\nu$	1.6M	8M
$Z\to ee$	160k	800k
$W\gamma$	1000	5000
$Z\gamma$	300	1500
WW	100	500
WZ	40	400
ZZ	few	30

Fermilab is a vector boson craft-workshop



With $\int \mathcal{L} dt = 10\ \mathrm{fb}^{-1}$, we will:

Study the edge of phase space!

Probe deep structure beyond 500 GeV

Measure IVB+jet production with high statistics

Understand multi-scale physics

Understand multi-gluon physics

Heavy quark production kinematics/dynamics

Probe jet structure

Understand multi-jet kinematics

NNLO calculational comparison

Understand diffractive scattering!

Support all other collider analyses with crucial background studies

Fermilab is a QCD conglomerate

Millions of events, period.

B physics

With $\int \mathcal{L} dt$ = 2 fb^{-1}, we will:

Measure CP violation in three modes

- B^0 $J/\psi K_s$
- B^0 $\pi\pi$
- B^0 $J/\psi\phi$

Measure | V_{td} | / | V_{ts} | from B_S mixing & $\Delta\Gamma_s$

Refine rare decay searches

- B $\mu\mu K$
- B $\mu\mu K^*$
- B_d $\mu\mu$
- B_s $\mu\mu$

Completely understand the B_C system

Completely understand B_s mixing

- Semileptonic decays
- Fully hadronic decays

Fermilab is a bottom quark industry

accepted/experiment			
channel		2fb^{-1}	10fb^{-1}
B mesons		10^{10}	5×10^{10}
B baryons		10^{8}	5×10^{8}
B_c		10^{9}	5×10^{9}
B^0	$J/\psi K_s$	15,000	75,000

There's more

Multiple inverse femtobarns make a qualitative difference:

Supersymmetry

and

the Higgs Boson

are accessible before the LHC

Supersymmetry–in words

The SM is extraordinarily successful

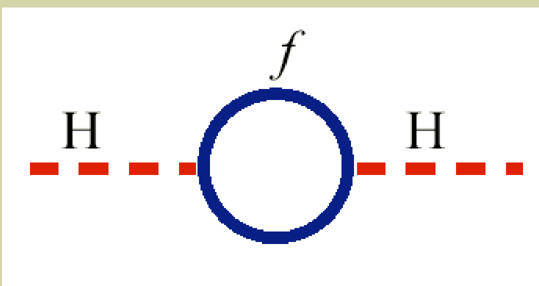
- nothing seems out of line…and yet nobody is happy.

Digging deeper is troubling

- SM: physics of the scale of the W/Z masses ~ 100 GeV, or distances of ~ 10^{-18}cm
- What about deeper scales? What are scale-milestones?

• Higgs is fat, due to radiative corrections

- problem is due to quartic self-interactions – which correct the mass of the Higgs



one loop contribution to the mass due to a fermion

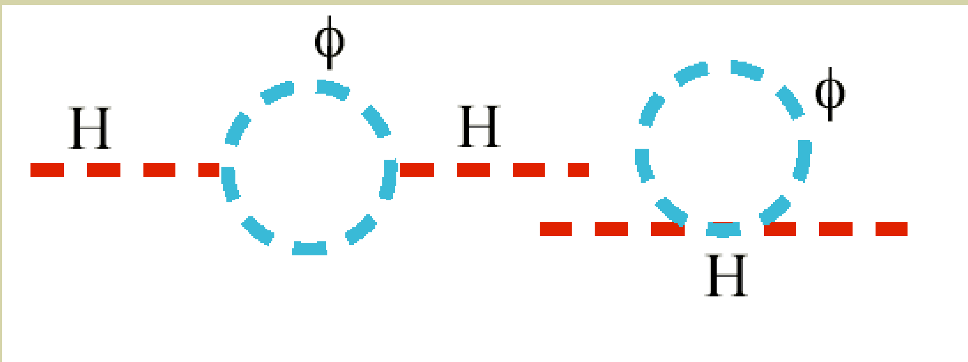
$$M_H^2 \sim \frac{\Box^2}{4\Box^2}\Box^2 + \frac{\Box^2}{4\Box^2} m_f^{\ 2}$$

The only high energy scale $\Box \sim M_{\mathrm{p}}$ is the Planck scale of 10^{18} GeV - no way to renormalize

Ugly...**the SM is fundamentally sick due to quadratic divergences**

Suppose the theory has Higgs, fermions, *and* additional scalars

- calculate their mass correction contributions



$$M_H^2 \sim -\frac{\lambda}{4\pi^2}\Lambda^2 + \frac{\lambda}{4\pi^2} m_\phi^2$$

a magical negative sign…cancels the divergent quantity if $\lambda_f^2 = \lambda$..and there is a pattern of $N(f) = N(\phi)$.

Then, the correction is $\frac{\lambda^2}{4\pi^2}\left(m_f^2 - m_\phi^2\right)$ so, equal masses means a total cancellation - a symmetry

Supersymmetry…in which $S\,|\,F> = |\,B>$

In practice, difficult

Supersymmetric partners for all particles

- With a spin flip…and a cute s-prefix
  - **Electron (spin 1/2) becomes selectron (spin 0)**
  - **Quark (spin 1/2) becomes squark (spin 0)**
  - **Photon (spin 1) becomes photino (spin 1/2)**
  - **Gluon (spin 1) becomes gluino (spin 1/2)**
- No SUSY at low energies, so supersymmetry is broken…search for their interactions at higher energies

This is not just silly…

- The Higgs mechanism is accounted for in a natural way and the Weinberg angle is predicted
- Unification of forces appears to work
- Superstrings contain SUSY...

A bold theoretical suggestion, on par with Dirac's positron, or Weinberg's *Z* !!

SUSY provides a unification of couplings

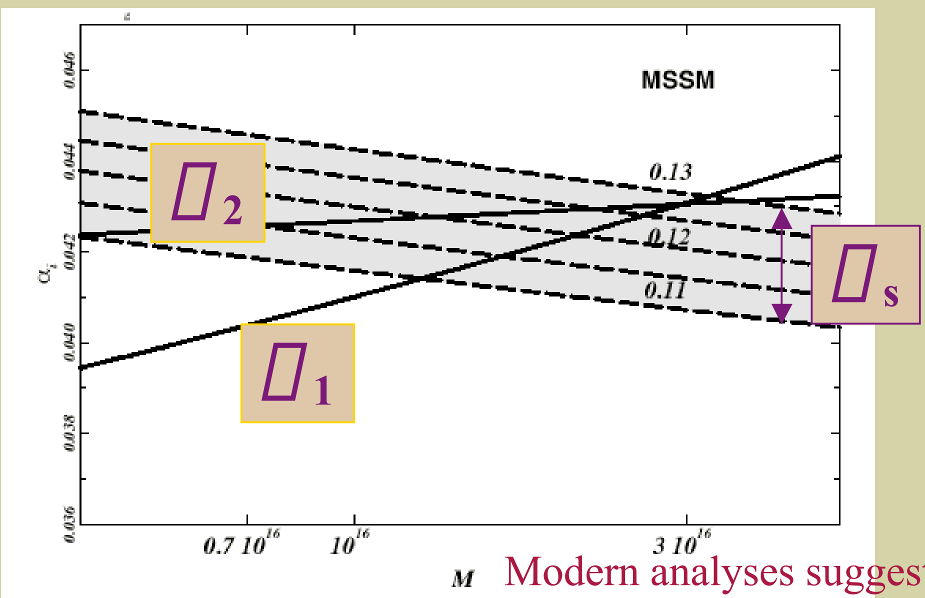
Unification – a goal – requires serious tinkering

Each force (electromagnetic, strong, and weak) is characterized by a coupling,

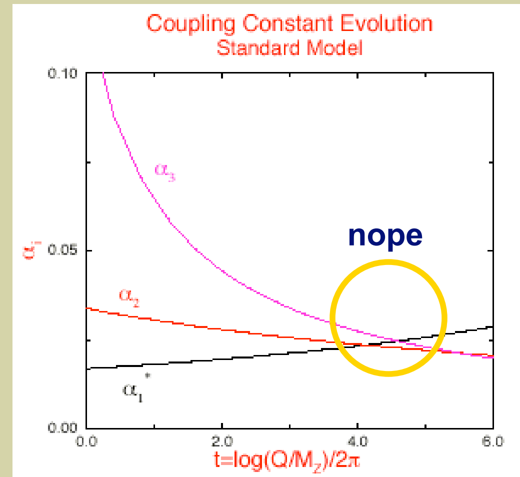
$\alpha_i(q)$ (I = 1,2,s), for

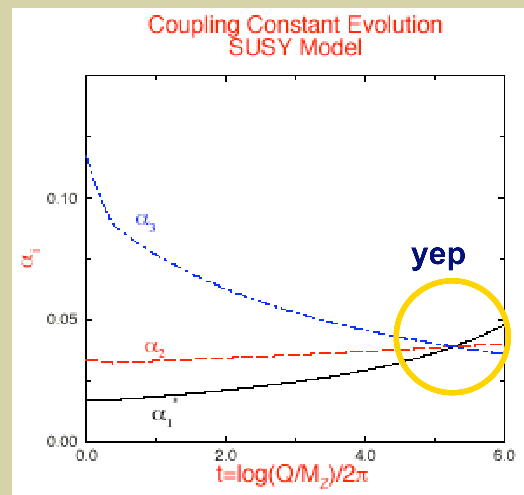
2 EW couplings and 1 QCD coupling

Unification requires that $\alpha_1(M_X) = \alpha_2(M_X) = \alpha_s(M_X)$



Modern analyses suggest $\alpha_s \approx 0.13$





SUSY is not the only solution…

- composite Higgs can protect itself from infinities (technicolor)

However, it is taken very, very seriously

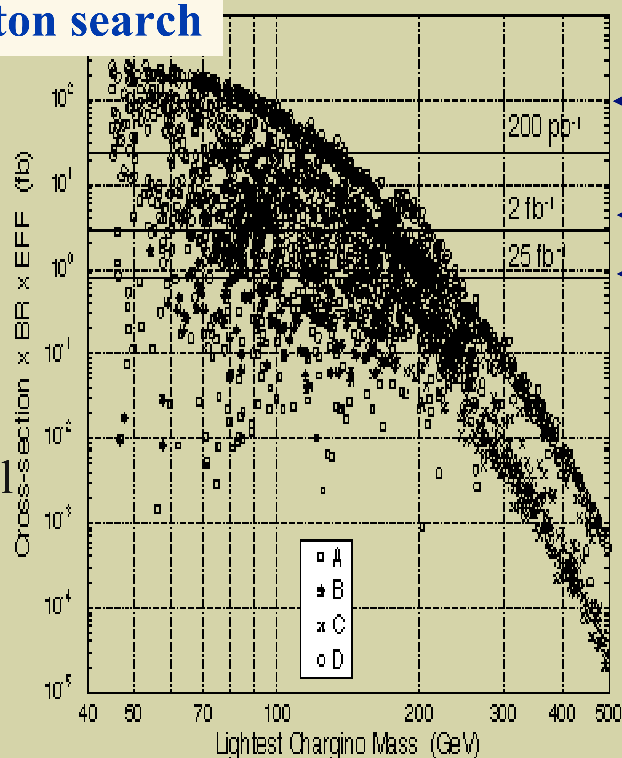
- Many flavors of models…thousands
- A particular brand is especially promising, called the Minimal SuperSymmetric Model (MSSM) contains definite predictions

1. 4 Higgs bosons, one of which is SM-like and must be lighter than ≈ 125 GeV/c^2
2. A supersymmetric “number” is conserved, so decays of SUSY particle result in another SUSY particle
3. A mass spectrum is conceivable, so there is a sterile Lightest SUSY state…which is missing energy in a detector
4. Signals are many leptons, and/or jets with significant missing energy

The time is right...

Model space

trilepton search



you are here

Run IIa

Run IIb

each dot, an allowed supersymmetric model

Dozens of limits have been set already by both experiments

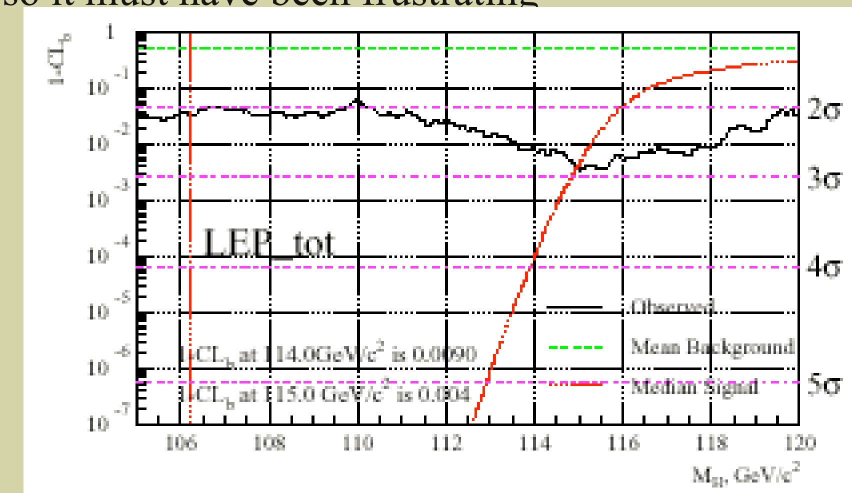
-ino	Predicted			actual
	Run I	2fb-1	10fb-1	Run I
$\chi^{\pm}$	65	~220	235	70
g	170	~360	400	270
t_1	48	150	155	145

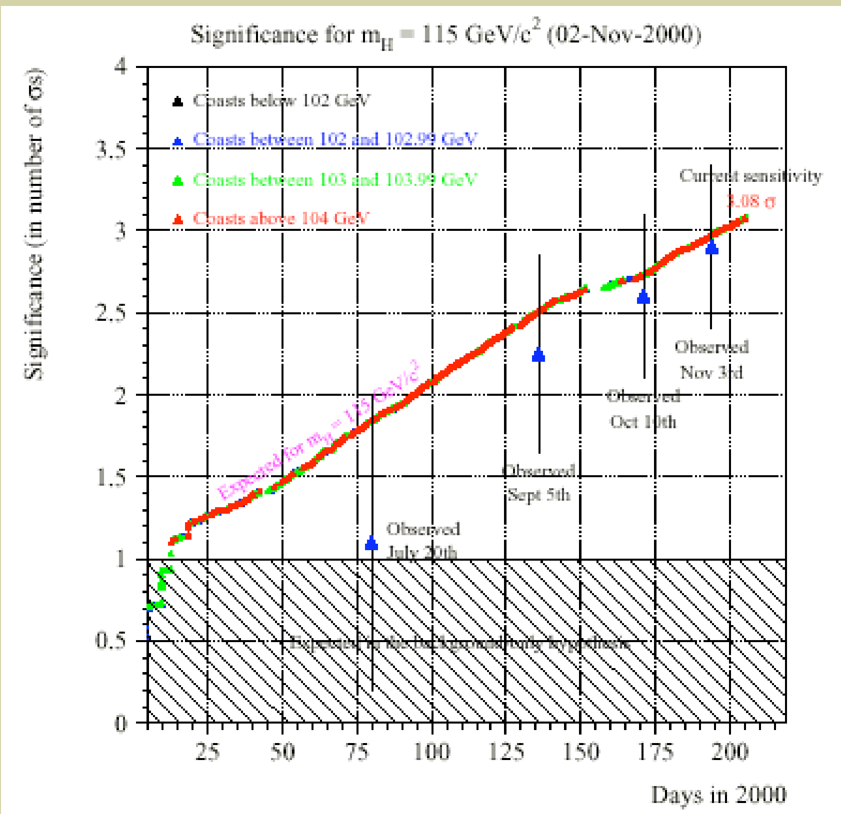
Fermilab could be a SUSY venture startup...

LEP 2 hints of the Higgs Boson

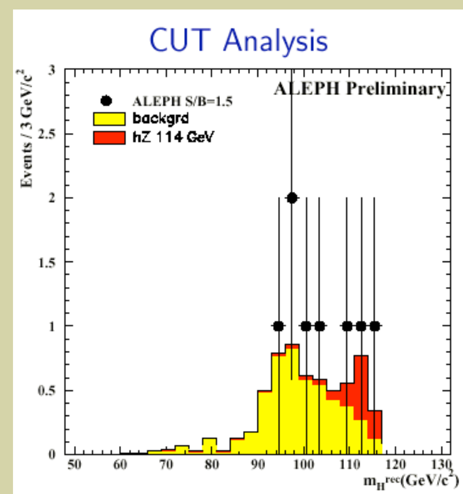
Hints appeared in September - a 1 month extension of the final running period was authorized...

- it experienced more than the average downtime, so it must have been frustrating
- Signal is associate production, *H(bb)Z(jj or ll)*.





the hint is a 2.9σ signal (all 4 experiments) at a mass of 115 GeV/c^2, with a 0.4% probability of it being background.

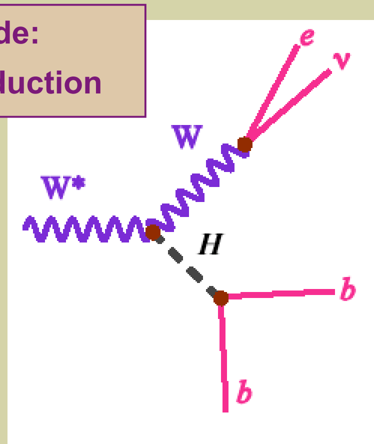


The HIGGS is the thing…

The Higgs couples to fermions via m_f - Big is beautiful..

Remember the EW connection? The SM seems to be pointing to a ***light Higgs boson***

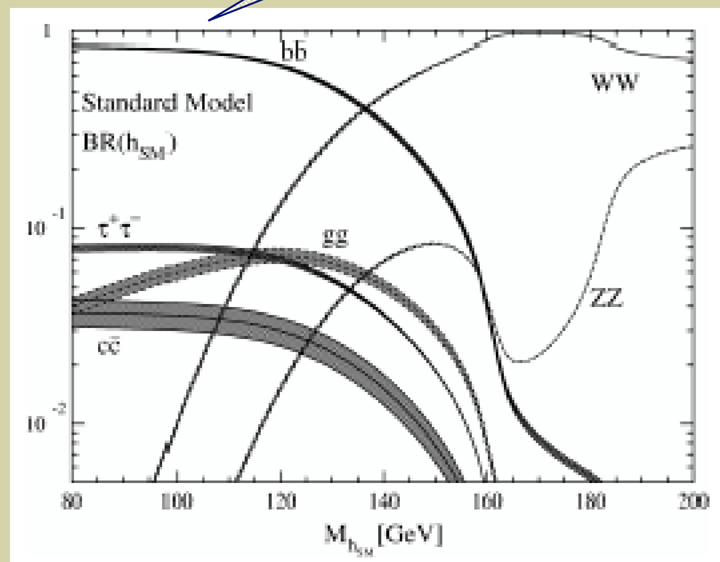
The Golden Mode: associated production



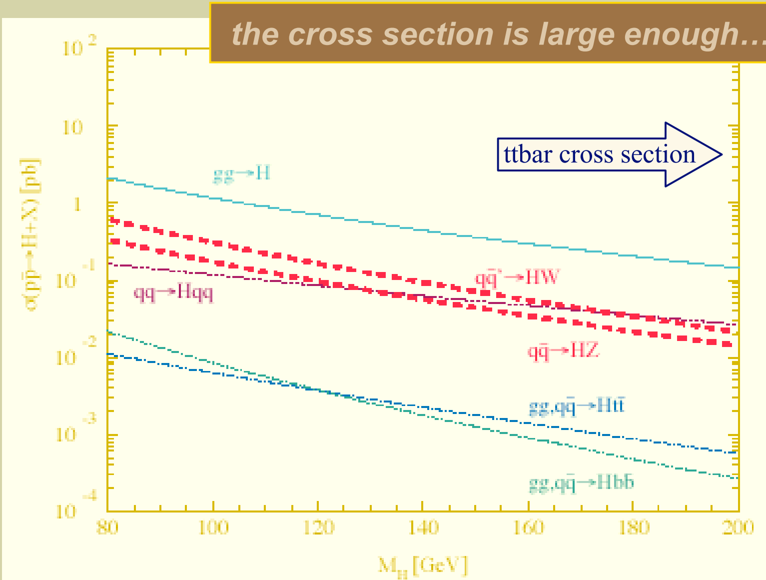
electron (or muon)

missing energy

two b's, at M_H



the cross section is large enough…

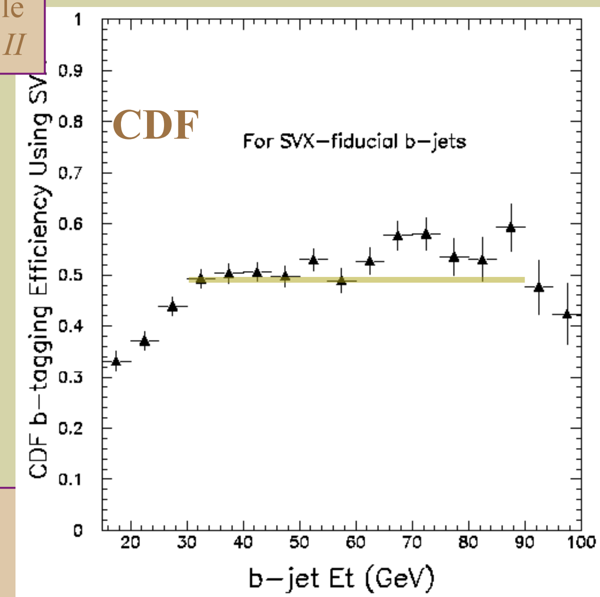


So, we expect a standard model Higgs boson:
- to be produced with an W and
- decay overwhelmingly to
  - b pairs (if light),
  - or 2W's (if slightly heavier…)

The issue is background from *pp* → *W+b+b*

Higgs could be ours...

B tagging efficiencies are already acceptable
Will be better in Run II

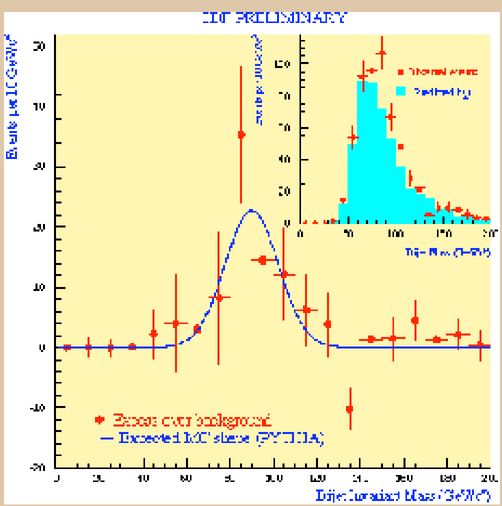


Need:

- Luminosity
- Ability to tag b's of relatively high p_T
- Ability to form $M(bb)$ with good resolution

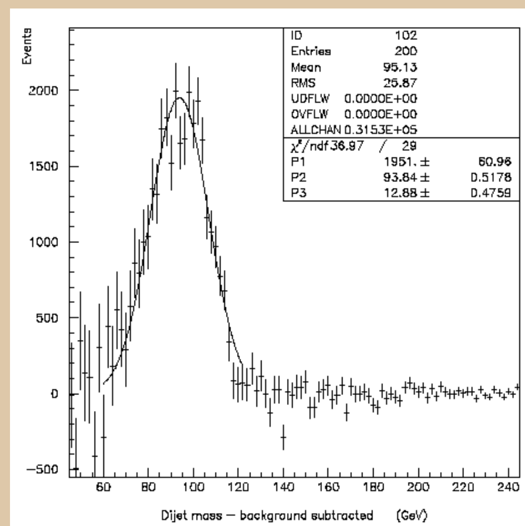
Mass resolutions will be acceptable

CDF study of $Z \longrightarrow bb$



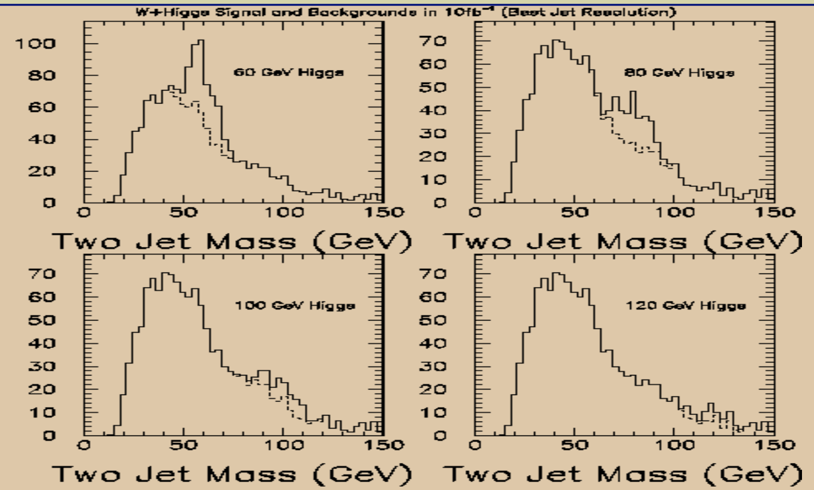
CDF MC
extrapolation to Run II

2fb^{-1}

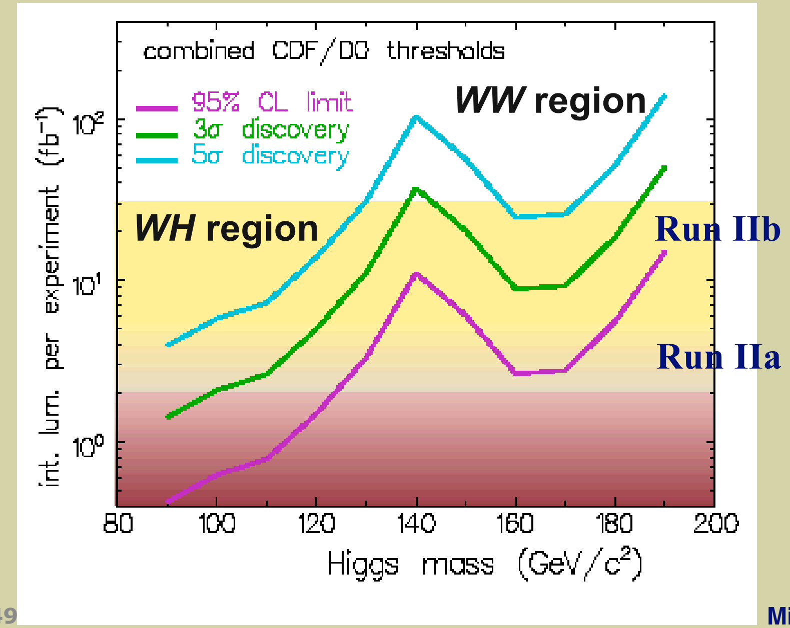


Higgs will be surrounded

$M(bb)$ in 10 fb^{-1}
$\Delta M \approx 8$ GeV
S/B ≈ 1/1, dependent on cuts
Mass resolution is key
top events
$Z \rightarrow bb$



Recently, a year-long workshop at Fermilab:



Fermilab could be a Higgs cottage industry

The plan is clear…

Run IIa

- Provides an ability to take the top quark apart
- Uncover CP violation in the B system
- Determine the *W* mass to precision necessary to corner the Higgs

Run IIb, above a critical *L* threshold of about 20pb^{-1}

- Maybe discover supersymmetry
- Maybe discover the Higgs Boson

If not there, then the more promising SUSY model is wrong, the SM EW model will be in jeopardy,

– *and a whole new era in elementary particle physics will have opened.*

If it is there, it will be studied at LHC, NLC, and/or a collider

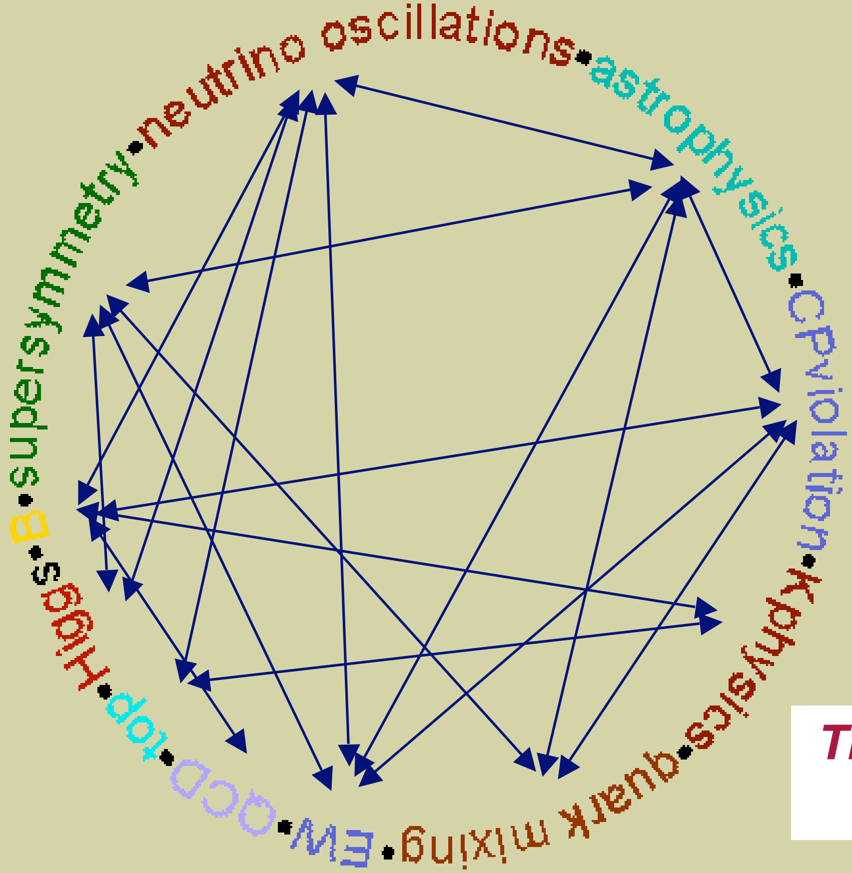
– *and a whole new era in elementary particle physics will have opened.*

A familiar no-lose situation again for Fermilab physics!

Conclusion

I've not talked about the Kaon CP program or the neutrino oscillation experiments

The <u>whole</u> program leads to evolutionary measurements blended with significant discovery potential - it's complete.



This is a great time to be at Fermilab